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- To gather, analyze, and present information that will aid decisionmakers in the identification and resolution of problems associated with major changes in land and water use.
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Volume II

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CHAPTER 8

EFFECTS AND MEASUREMENT OF FRESHWATER INFLOW

THE INFLUENCE OF SALINITY TRANSITION ON BENTHIC NUTRIENT REGENERATION IN ESTUARIES

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ABSTRACT

Benthic nutrient regeneration, the liberation of nutrients (particularly N and P) from sediments to overlying water, is quantitatively important in estuarine nutrient budgets. Regeneration rates can be significantly affected by the physical and chemical parameters of the overlying water. Alterations of freshwater inflow result in salinity transitions in which these parameters are changed, and therefore they are likely to cause changes in nutrient regeneration rates. The rates at which sediment nutrients are mineralized, mobilized, and released are controlled by complex interrelationships between biological processes, such as community metabolism and organism activities; and physical/chemical mechanisms, such as the effects of salinity, pH, and redox potentials on sorptive processes. Due to the importance of nutrient cycles in the overall functioning of estuarine ecosystems, any appraisal of the consequences of changes in freshwater inflow to an estuary should include consideration of the effects on benthic nutrient regeneration.

INTRODUCTION

Recent research has shown that benthic nutrient regeneration, the flux of nitrogen and phosphorus from sediments to overlying water, plays an important role in the nutrient cycles and budgets of both marine ecosystems (Rowe et al. 1975; Davies 1975; Hale 1975; Hartwig 1976; Nixon et al., 1976; Rowe et al. 1977) and freshwater environments (Kamp-Nielsen 1974; Banoub 1977; Lee et al. 1977; Stevens and Gibson 1977; Holdren and Armstrong 1980). Evidence for the importance of sediment nutrient flux in estuaries (Pomeroy et al. 1965; Upchurch et al. 1974; Stirling and Wormald 1977) has been neither as extensive nor as direct. However, it is most likely that sediment nitrogen and phosphorus fluxes are equally or even more important in most estuarine ecosystems, since estuarine sediments usually have high organic content which permits high rates of biological metabolism (i.e. Carter et al. 1973) and which results in high sediment inorganic N and P concentrations (Brooks et al. 1971; Ho and Lane 1973; Upchurch et al. 1974; Matisoff et al. 1975). For example, Taft and Taylor (1976) suggested that sediment P flux was the major source of dissolved phosphate in Atlantic coastal plain estuaries and that it controlled the annual cycle of phosphate concentration. The fact that most estuaries are relatively shallow and thus have a high sediment-surface to water-volume ratio furthers the relative importance of sediment nutrient flux.

Many of the processes involved in benthic nutrient regeneration can be affected in the estuarine environment by parameters directly related to the degree of sea water dilution by freshwater inflow. In all estuaries, freshwater inflow results in a spatial salinity transition, with salinity increasing from the head of the estuary, or freshwater source, to the mouth of the estuarine ecosystem. Temporal salinity transitions also occur in most estuaries and often are related to seasonal climatological patterns which cause changes in freshwater inflow. Although salinity transition can have other causes such as evaporation, wind stress, seasonal tidal patterns, or modification of estuarine geomorphology, in the following discussion estuarine salinity transition will be considered to be that arising from changes in freshwater inflow. Very often the transitions are large in magnitude and extensive in area and can have profound effects on the functioning of estuarine ecosystems.

Among the parameters that can be affected are those which influence the rates of nutrient flux from sediments. Because nutrient levels can control rates of estuarine productivity (Williams 1972) and because productivity in turn can greatly influence the biological functioning of an estuary, it is very important that any assessment of the effects of freshwater inflow to an estuary include consideration of its potential effects on sediment nutrient regeneration and the resulting effects on the nutrient cycles of the estuarine ecosystem.

In order to evaluate these effects it is important to understand the mechanisms by which salinity transition can affect nutrient regeneration. For the most part, the mechanistic responses to salinity transition can only be inferred from the mechanisms themselves, as very little experimental or empirical data are available. This is an area of estuarine ecology that is acutely in need of further research.

SEDIMENT NUTRIENT MINERALIZATION PROCESSES

The cycles of N and P in sediments can be divided into three categories of processes: mineralization processes, mobilization processes, and release processes. Mineralization processes are those processes which transform organic N and P into forms which can be liberated from the sediments, while mobilization processes are those which transform mineralized nutrients into forms which permit or enhance the release processes by which the actual liberation occurs. Sediment N and P can originate from several sources, including coagulation and sedimentation of colloidal suspensions such as clay minerals (Edzwald et al. 1974) to which inorganic N and P may be adsorbed (Upchurch et al. 1974); depositon of allochthonous mineral detritus such as apatite (Rittenberg et al. 1955; Wentz and Lee 1969); and direct sorbtion of inorganic N and P from overlying water (Pomeroy et al. 1965; Stirling and Wormald 1977). However, sediment nutrient flux typically derives mostly from inputs of allochthonous and autochthonous organic material.

Before the nutrients contained in these organic materials can be released from the sediments they must be mineralized to inorganic forms such as ammonia or phosphate or at least transformed into soluble organics, primarily by the metabolic activities of the heterotrophic community within the sediment. This biological mineralization can be described (Head 1976), assuming that the mineralized organic material has a composition similar to marine plankton (Redfield et al. 1963), for the case of oxygenated environments by:

$$(CH_2O)_{106} (NH_3)_{16} H_3PO_4 + 106 O_2 \rightarrow 106 CO_2 + 16 NH_3 + H_3PO_4 + 106 H_2O.$$

In anaerobic sediments, where microbial sulfate reduction predominates, the relationship is:

$$(CH_2O)_{106} (NH_3)_{16} H_3PO_4 + 53 SO_4^{2-} \rightarrow 106 CO_2 + 16 NH_3 + H_3PO_4 + 53 S^{2-} + 106 H_2O.$$

Therefore, sediment biological metabolism results in formation of ammonia and phosphate which potentially can be regenerated. Numerous studies have shown that bacterial metabolism is the largest component of the total metabolism of benthic communities (Teal and Kanwisher 1961; Pamatmat 1968; Smith 1973; Edwards 1977), and since almost all of the metabolized detrital organic material is originally broken down by microbial decomposers; in most cases it is reasonable to consider the microbial component as being most important to mineralization. However, other components of the community such as protozoa (Johannes 1965) or meiofauna (Tenore et al. 1977; Tietjen 1980) can directly or indirectly affect mineralization rates. Overall, the rate of mineralization theoretically and empirically should be closely correlated with total community catabolic metabolism; or more simply said, the greater the rate of sediment biological activity, the greater the rate of mineralization.

In addition to total metabolic rate, other factors, such as the physiological state of the community, are also important to the mineralization rate. For example, a steady-state community in which biomass is neither increasing nor decreasing will mineralize nutrients in close relationship to its total metabolic rate. On the other hand, a rapidly growing population, like a microbial population in logarithmic growth phase, may incorporate much of the nutrients in the mineralized material into protoplasm; and thus, despite its high metabolism, could have a low mineralization rate or could even function as a nutrient sink by assimilating inorganic nutrients (Thayer 1974). Also, the relative proportion of the types of metabolic pathways may be important in determining the rate of mineralization relative to total metabolism. For example, in marine sediments sulfate reduction can account for over half of the total sediment metabolism (Jorgensen 1977). However, sulfate reducing bacteria can only use a limited number of low molecular weight compounds as energy sources, primarily lactic acid and pyruvic acid which they oxidize to acetate (Goldhaber and Kaplan 1974). Therefore, sulfate reduction itself should not yield mineralized N or P, although it may greatly affect mobilization and release as discussed below.

EFFECTS OF SALINITY TRANSITION ON MINERALIZATION RATES

There are a number of ways by which salinity transition can affect N and P mineralization rates. For those portions of an estuary that seasonally experience transition from limnetic (0.5 ppt) (Symposium on the Classification of Brackish Waters 1958) to estuarine conditions, the question is whether metabolism and therefore mineralization are comparable under both conditions. Hargrave (1969) offered empirical evidence that the respiration of marine and freshwater benthic communities is similar relative to temperature, which he hypothesized to be the controlling variable by its affect on the rate of diffusion of oxygen into sediments. With the exception of one study (Hanes and White 1968), which found that respiration of benthal deposits increased with increasing salinity during short-term incubations, there have been no experimental studies of the effect of salinity on benthic metabolism.

Even if acclimated freshwater and brackish-water sediments can have relatively equal metabolic and mineralization rates, these rates may be significantly changed during periods of salinity transition. One result of transition may be faunal succession in which better adapted species, or strains in the case of bacteria (Ochynski and Postgate 1963), replace existing fauna. However, the succession may be incomplete, in that replacement may not occur rapidly enough to maintain the previous rates of community metabolism and mineralization. On the other hand, the main effect of transition may be the imposition of stress (Odum 1971) or equivalently incomplete acclimation (Prosser 1973) on a euryhaline fauna. The effect of salinity stress on an estuarine organism may be to either increase or decrease metabolism (Vernberg and Vernberg 1972), and thus incomplete acclimation may result in either increased or decreased mineralization rates. Therefore, salinity transition may result simultaneously in incomplete succession, which tends to decrease mineralization rates, and incomplete acclimation, which may either decrease or increase them, with the net community response being a function of the relative magnitude and direction of these two factors. Due to this complexity and given the present limited scientific knowledge, no generalizations can be made except to say that estuarine salinity transition can have significant effects on sediment biological activity and therefore on mineralization rates. Further research is needed before the direction and magnitude of these effects can be predicted.

SEDIMENT NUTRIENT RELEASE AND MOBILIZATION PROCESSES

In order for mineralized nutrients to be regenerated, they must be liberated from the sediments. The category of processes by which this transfer occurs can be called release processes.

RELEASE BY MOLECULAR DIFFUSION

The principal mode by which nutrients are released from sediments is molecular diffusion. The diffusional flux of a nutrient species between sediment and overlying water follows Fick's first law of diffusion:

$$J_x = -D_s \, \phi \, \frac{\partial C}{\partial x} \bigg| \, x = 0$$

where J_x = the diffusional flux in mass/area of sediment/time, D_s = the empirical whole sediment diffusional coefficient, ϕ = the porosity of the sediment, C = the concentration of the nutrient in mass per unit volume of porewater, x = the unidimensional depth coordinate (Berner 1971).

MOBILIZATION OF SORBED NUTRIENTS

Mobilization processes can be defined as those transformations which facilitate release processes and/or make them possible. Because diffusion and most other release processes involve transfer of the dissolved constituents of sediment porewater, the most important mobilization processes are those which transform inorganic nutrients into dissolved forms. Sediment inorganic nutrients that are not dissolved are either sorbed to sediment particles or precipitated. In most cases, dissolution of precipitated minerals does not play a major role in nutrient release (Williams 1972) and therefore will not be discussed further. In contrast, sorbtive processes play a very important role in nutrient regeneration (for details see Berner 1974 and 1977), and for that reason mineralized nutrients are not directly and passively released through diffusional flux directly in proportion to their rate of production by mineralization processes. Therefore, the most important mobilization processes are those which affect nutrient sorption.

According to Carritt and Goodgal (1954) sorption can be defined as any reaction between a solid and a dissolved substance, while adsorption is a free energy decreasing accumulation on a solid surface, of an environmental constituent at a greater concentration than exists at a distance from the surface. Rosenfeld (1979) found that K, the ratio of adsorbed ammonia to dissolved porewater ammonia, in marine sediments was between one and two, which is to say that on a per unit of sediment basis up to twice as much ammonia is adsorbed to solids as is dissolved in pore water. The K for phosphate in anoxic marine sediments has been shown by Krom and Berner (1980) to be similar to that for ammonia, but they also found that in oxic sediments K_p was more than an order of magnitude greater.

EFFECTS OF SALINITY ON ADSORPTION

The sorptive capacity of sediments can be affected by salinity. Carritt and Goodgal (1954) and Stirling and Wormald (1977) found that salinity had a pronounced effect on estuarine sediments' sorptive capacity for phosphorus. In both studies sorption decreased with increasing salinity, and although the mechanism has not been clearly demonstrated, it probably is due to a combination of fine particle agglomeration with increasing salinity and resultant reduction of surface area available for P adsorption, and competition for adsorption sites between PO_4^{2-} and other anions that increase in concentration with increasing salinity (Carritt and Goodgal 1954).

EFFECTS OF pH ON ADSORPTION

In addition to the direct effects of salinity, nutrient adsorption can be influenced by pH which in turn can be affected by salinity. Although pH may have some effect on sediment ammonia adsorption(Kamp-Nielsen 1974), it is phosphate that is most strongly affected. Results of studies by Carritt and Goodgal (1954), Jitts (1959) and Stirling and Wormald (1977), using suspended estuarine sediments from Chesapeake Bay, Australia, and Hong Kong were remarkably similar, showing decreases in adsorption at pH less than about 3 or greater than about 6. Kamp-Nielsen (1974) found that the highest rate of P release from anaerobic lake sediments occurred at pH 6.5 to 7.0. Even small pH changes have been shown to substantially affect P adsorption (Nur and Bates 1979). The mechanism by which pH varies the P-binding capacity of oxgenated sediments involves decreased binding at higher pH due to competition by hydroxl ions with phosphate ions for binding sites on the iron (III)-hydroxide complex (Lyklema 1977) which is the principal P-adsorbing component in many oxic sediments.

There are two major ways in which salinity transition can result in pH changes which in turn can affect adsorption. First, dilution of seawater by fresh water decreases bicarbonate concentration, reducing buffering capacity and thus permitting wider pH ranges to occur in the overlying water. Second, salinity transition can result in changes in the types and relative importance of sediment metabolic pathways. For example, Ben-Yaakov (1973) presented theoretical evidence that the pH of porewater in anoxic marine sediments is buffered to fall within the range of 6.9 to 8.3, depending upon the fate of sulfide produced during sulfate reduction. However, in oligohaline estuarine sediments sulfate reduction may be limited by sulfide concentration; and therefore other processes, such as anaerobic microbial fermentation in which organic acid formation and methanogenesis predominate organic decomposition may cause a different pH regime.

EFFECTS OF OXIDATION-REDUCTION POTENTIAL

Oxidation-reduction or redox potential is another parameter which is very important in controlling sediment nutrient flux. Oxidation-reduction potential can be defined as a quantitative measure of electron escaping or oxidation tendency of a reversible oxidation-reduction system, or equivalently as a measure of how reducing or oxidizing a system is with reference to some standard (Zobell 1946). Redox potential is controlled to a large degree by biological activities in the sediment (Morris and Stumm 1967). For example, Berner (1963) showed that in anoxic marine sediments redox potentials are controlled by the concentration of sulfide that is formed by anaerobic bacterial sulfate reduction.

The present concept of phosphorus regeneration is based on Mortimer's (1941 and 1942) studies in which he showed that nutrients, especially P, were liberated from lake sediments when redox potentials were lowered due to oxygen depletion of the hypolimnion during seasonal thermal stratification. Elucidation of the mechanism controlling sediment P release under low redox conditions began with early observations of the intimate relationship between phosphorus and iron (Ohle 1937, Einsele 1938) and has been thought to involve reduction and solubilization of ferric compounds to which phosphate is sorbed or by which it is precipitated (Mortimer 1941 and 1942, Hutchinson 1957, Khalid et al. 1978). Recent evidence indicates that formation of discrete phases of iron phosphate is of little significance and thus that sorptive processes predominate (Syers et al. 1973), with most inorganic P associated with amorphous Fe oxides or hydroxides (Williams et al. 1971, Shukla et al. 1971). There have been many recent studies confirming Mortimer's (1941 and 1942) observations of the importance of sediment redox potential to P release (Schipple et al. 1973, Patrick and Khalid 1974, Lee et al. 1977, Khalid et al. 1978), and as previously mentioned, Taft and Taylor (1976) have suggested that summer dissolved P increases in Chesapeake Bay are the result of redox mediated sediment P flux occurring when deeper bay waters become oxygen depleted.

The classic limnological paradigm of sediment P release (Mortimer 1941, 1942, and 1971) is that a superficial, oxidized sediment microzone can act as almost a total barrier to P flux, with practically no P flux occurring under oxic conditions. In addition, although a mechanism was not proposed, it has been suggested that oxidized sediments may present a similar barrier to the diffusion of interstitial ammonia to overlying water (Graetz et al. 1973). However, recent studies of lake sediments (Lee et al. 1977) and marine sediments (Hale 1975, Hartwig 1976) have shown that anoxic conditions only serve to accelerate release, since substantial fluxes of N and P were measured under oxic conditions. This may be because a thin, superficial layer of oxidized sediment can be a barrier only to the extent to which it contains enough ferric hydroxide and other sorbing complexes to effectively sorb all of the biologically mineralized nutrients diffusing from deeper anoxic layers. In sediments with low Fe content and high mineralization rates, the mere existence of a superficial oxidized layer may not be sufficient to present a barrier to P release; the actual thickness and thus total sorptive capacity of the oxidized zone may control the rate of P flux to the overlying water. However, if the oxidized zone exists for a long period of time, ferrous ions can diffuse to it, and be oxidized and accumulate (Berner 1969).

There are several ways in which salinity transition can affect sediment oxidation-reduction potentials and thus affect nutrient release. Any transition-caused changes in the magnitude of total sediment metabolism can potentially affect redox conditions due to the aforementioned relationship between biological activity and redox potential. It is likely that in oligohaline portions of estuaries, transition can have a direct effect on sediment redox potentials by limiting the rate of sulfate reduction in anaerobic sediments, which in turn controls sediment sulfide concentration and thus redox potential (Berner 1969). Although the sulfate reduction rate in sediments is limited by sulfate concentration only at low concentrations and perhaps not until sulfate is less than 1.2 micromole (mM)/liter (Berner 1974), which is 4% of the 28 mM/liter concentration found in undiluted seawater, analyses based on kinetic diffusion models (Berner 1974, Kleiber and Blackburn 1978) and estimates of sulfate reduction rates (Jorgensen 1977) predict that porewater sulfate would reach limiting concentrations even when the overlying water sulfate concentration is much greater than 1.2mM/liter.

In summary, the major effect of salinity transition, for the case of increasing salinity in oligohaline environments, is to increase the rate of sulfate reduction which then increases dissolved sulfide concentration which in turn reduces the sediment redox potential. The decrease in redox conditions would then eliminate or diminish the superficial oxidized layer, mobilizing nutrients, particularly P, which previously were sorbed within the oxidized layer, and thus permit diffusive flux to the overlying water. The case of transition to lower salinity would be expected to cause a reversal of these processes, although, as discussed below, porewater sulfate concentration would not change as rapidly.

A final mechanism by which salinity transition could influence redox potentials is by affecting the structure of the existing infaunal community which through bioturbation can maintain oxidized sediment conditions (Edwards 1958, Hargrave 1972).

OTHER RELEASE PROCESSES

In all of the above discussion, mobilized nutrients have been assumed to be released via diffusion. However, there are several other physical release processes which may affect nutrient flux rates in estuaries. A process that may be very important in estuarine environments that undergo large salinity transitions is convective, density-gradient driven overturn of sediment porewater (Scholl 1965, Scholl and Johnson 1967; Lindberg and Harriss 1973). During periods of higher salinity incursions, high-density overlying water displaces less dense (lower salinity) porewater and thus may effectively pump nutrient-rich porewater out of the sediment. Such convective overturn can be rapid relative to the much slower process of diffusion (R.E. Edwards unpublished data). Therefore, the effects of transition to higher salinity should occur more rapidly and should be more acute than those of transition to lower salinity. Another nondiffusional mechanism of nutrient release is bioturbation by infauna such as Chironomus larvae, oligochaetes, polychaetes, and bivalve mollusks, which can affect both oxygen and nutrient fluxes (Edwards 1958, Hargrave 1972, Aller and Yingst 1978) by pumping associated with burrow or tube irrigation and with feeding. As mentioned above, salinity transition may result in changes in benthic infaunal community composition and thus in the magnitude of bioturbation effects. Finally, in low salinity areas sulfate reduction may be sufficiently limited to allow methane formation to predominate or occur in deeper sediments (Reeburgh and Heggie 1977), and CH_4 bubble formation and ebullition can occur and can greatly increase nutrient fluxes (Martens et al. 1980). Thus the aforementioned effects of salinity transition on the relative versus that of methanogenesis will also influence the rate of nutrient release by this mechanism.

SUMMARY AND CONCLUSIONS

Any variation in freshwater inflow to an estuary will to some extent result in spatial and temporal salinity transitions. Such transitions are among the characteristics unique to estuaries and can have profound effects on the functioning of benthic communities. Although there has been little direct research specifically on the effects of salinity transition on estuarine community functioning, the present understanding of the processes and mechanisms which control functioning in marine and freshwater sediment systems can be used to deduce the responses of estuarine benthos to salinity transition. Sediment nutrient regeneration is one of the aspects of community functioning that can be deduced to be significantly influenced by transition, based on direct evidence of the importance of benthic nutrient regeneration (particularly N and P) to the nutrient cycles of freshwater and marine ecosystems, and on preliminary observations in estuaries. Given the essential role of nutrient cycles in determing estuarine structure and functioning, it is imperative that any appraisal of the consequences of changes in freshwater inflow to an estuary include consideration of the effects on benthic nutrient regeneration.

Sediment nutrient regeneration can be divided into three categories of processes: (1) mineralization processes that transform nutrients contained in sedimented organic matter into dissolved inorganic forms that can be liberated; (2) mobilization processes that facilitate or make nutrient release possible and ; (3) release processes by which the physical liberation occurs. All of these processes can be significantly affected by salinity transition. Mineralization occurs primarily through biological processes, and therefore almost any effect of salinity transition on the biology of the benthic community can have ramifications that influence mineralization rates. Mobilization is particularly significant because of the importance of sediment sorptive processes which can effectively immobilize nutrients by removing them from solution in porewater and thus make them unavailable to release processes. Salinity transition can influence mobilization either directly through physical/chemical mechanisms, or indirectly through its effects on biological functioning which in turn affect the physical/chemical parameters. The predominant nutrient release process is molecular diffusion. For the most part, salinity can only affect diffusional flux indirectly through its effects on mineralization and mobilization which control the porewater nutrient concentrations of which diffusional flux is a direct function. However, other release processes such as convective overturn, bioturbation and ebullition are greatly influenced by salinity transition.

Overall, estuarine sediment nutrient regeneration depends on an interrelationship between biological and physical/chemical processes, which due to its complexity makes generalization or prediction concerning the effects of salinity transition very difficult. Based on the scientific evidence available, only the following generalizations seem obvious: (1) The effects of salinity transition should be a function of both the absolute value of the salinity change and the rate at which change occurs, with greater effects from larger and more acute changes.

(2) Due to the rapidity of convective overturn relative to the much slower process of diffusion, transition to increased salinity should cause changes in system functioning to occur more rapidly and therefore should result in more immediate changes in nutrient regeneration. (3) Salinity transition should have the greatest functional impact when it occurs in the oligohaline (0.5 to 5.0 ppt) portion of an estuary. Due to the numerous fundamental biological and geochemical differences between freshwater and marine systems, oligohaline benthic environments should be particularly sensitive to salinity changes that can make their structure and functioning more like that of either marine or freshwater systems.

Before additional generalization or prediction can be made, further research on the effects of salinity transition on benthic communities is needed, particularly the following: (1) Almost any research elucidating the effects of salinity transition on biological functioning would be useful. Further quantification of the role of sulfate reduction in oligohaline transitional environments would be especially valuable. (2) Additional research on geochemical pathways and transformation processes is sorely needed, particularly concerning the role of iron, clay minerals, and organics in sorptive reactions and on the effects of redox potential on these sorptive processes. (3) Generalization and prediction of the responses of estuarine benthic systems to salinity transition can be reached most immediately and directly through an empirical approach utilizing field studies that monitor transitional changes in parameters such as benthic community structure; benthic community metabolism, as estimated from in situ measurements of oxygen consumption and sulfate reduction rates; quantitative fractionization of the different forms of sediment N and P; and sediment N and P fluxes, as determined directly by in situ measurement.

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MONITORING FRESHWATER INFLOW TO ESTUARIES BY REMOTE SENSING

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ABSTRACT

Experiments conducted in the United States coastal zone indicate that features such as plumes from freshwater inflow have distinctive spectral characteristics. These spectral characteristics have been correlated with concentrations and/or distributions of temperature, salinity, suspended solids, and chlorophyll a in plumes and surrounding estuarine water. Remotely sensed wide area synoptic coverage of surface estuarine features provides a perspective on spatial and temporal distributions that is not readily available by shipboard measurements. Data outputs from remote sensors, to date, include (1) high resolution measurements to determine concentrations and distributions of total suspended particulates, temperature, salinity, and chlorophyll a from airborne and/or satellite platforms; and (2) low resolution measurements of total suspended solids, temperature, and possibly chlorophyll from satellite platforms. Archived data (such as from Landsat) may be used for historical studies of river plumes and other estuarine features. Examples are presented in which remotely sensed optical and microwave spectral range data, with and without concurrent surface measurements, are used to study spatial and temporal characteristics of plumes. In general, qualitative assessments may be made without concurrent surface measurements based on differences of water color, temperature, and salinity within the plume or between the plume and the receiving water. Quantitative distribution of suspended solids, temperature, salinity, and chlorophyll a require concurrent surface measurements to calibrate the remotely sensed data.

INTRODUCTION

Experiments conducted in United States coastal zones indicate that certain pollution and oceanographic features have distinctive spectral characteristics. Remotely sensed wide area synoptic coverage provides information on these features that is not readily available by other means. Data outputs from sensors may be analyzed and interpreted to provide information of interest to oceanographers and environmental managers. This information includes (1) synoptic high resolution surface measurements of particulates, salinity, temperature, chlorophyll a, and possibly phytoplankton diversity from airborne multispectral (optical range), passive microwave and active laser systems and (2) repetitive ocean surface data from environmental and meteorological satellites (Landsat, AEM-A, NIMBUS 7, TIROS, etc.). Airborne and satellite (Landsat) based sensors appear to provide adequate spatial resolution to meet the needs of estuarine experiments (Johnson and Harriss 1980), while the low resolution of the present oceanographic and meteorological satellites limits their application in these nearshore areas (McClain 1977). Characteristics of airborne and satellite remote-sensing systems are summarized in Tables 1 and 2, respectively.

Various investigators have applied classification or regression techniques to calibrate satellite (Landsat) and aircraft multispectral scanner data and to map distributions of water quality parameters in inland and coastal zone systems (Williamson and Grabau 1973, Yarger et al. 1973, Klemas et al. 1974, Bowker et al. 1975, Rogers et al. 1975, Johnson 1978, and Johnson and Bahn 1977). Subsequently, experiments were conducted in the United States coastal zone to determine the applicability of aircraft and satellite remote-sensing systems (1) to locate, identify, and map features without the requirement for concurrent sea-truth measurements and (2) to evaluate previously developed analysis techniques for determining quantitative distributions of specific parameters. As a part of (1) above, multispectral-analysis techniques were developed that may be used to identify features at a variety of locations and to assess the effects of environmental conditions (e.g., sun brightness and elevation, atmospheric haze, and background) on the analysis and interpretation of remotely sensed data (Johnson 1977).

Remote sensing in the microwave spectral range from airborne platforms has been reviewed by Swift (1980). Experiments using L and S band (1.43 and 2.65 GHz) radiometers have been conducted by the National Aeronautics and Space Administration's (NASA) Langley Research center to determine distributions of salinity and temperature. These measurements, which are based on "microwave brightness" radiation measurements, may be made over a wide range of environmental conditions (e.g., cloudy and hazy days, or at night), thus increasing the opportunity for monitoring the coastal zone.

Evaluations of active systems include the Airborne Lidar Oceanographic Probing Experiment (ALOPE) (Brown et al. 1978) which measures the induced fluorescence resulting from sequential excitation by lasers in four optical range spectral bands to estimate total chlorophyll a concentrations and chlorophyll distribution among four phytoplankton color groups (green, golden brown, red, and blue-green) thereby providing a measure of phytoplankton diversity. Following successful laboratory evaluation, this instrument is in the early stages of a field evaluation program. As an active system, the ALOPE is not limited to daylight or clear weather operation, as in the case of passive optical systems which depend on reflected radiation. Concurrent surface measurements of water attenuation coefficients are required for instrument calibration.

Investigations by Bowker and Witte (1977), using Landsat data, indicate similar analysis techniques are applicable to digital data from aircraft and satellite systems. In the spacecraft data, features with high radiance contrast such as river discharges and ocean disposal plumes are readily discernible. Repetitive Landsat data have been analyzed by Klemas et al. (1974) to study coastal water turbidity and circulation patterns in the vicinity of the Delaware Bay.

Table 1. Aircraft platforms, sensors, and oceanographic parameters.

Aircraft and Sensor Characteristics						Oceanographic Parameter, Range (accuracy)				
Fixed wing Aircraft (Typical)	Altitude, km (Typical)	Sensor	Spectral Range	Spatial Resolution (at Nadir) m	Swath Width, km	Suspended Solids, mg/ℓ	Chlorophyll a Conc., mg/m^3	Chlorophyll a Diversity	Temperature Degrees C	Salinity ppt
U-2	19.7	OCS	VIS, NIR	75	25	>5 (±5)	>2 (±2)	-	-	-
		Cameras	VIS, NIR	10	25	Qual.	Qual.	-	-	-
C-130	3.0	M2S	VIS, NIR	8	8.5	>5 (±5)	>2 (±2)	-	-	-
			TIR	8	8.5	-	-	-	0-35 (±2)	-
		Cameras	VIS, NIR	0.5	4.5	Qual.	Qual.	-	-	-
P-3	1.4	MWR	MW	500	500m (Line)	-	-	-	0-35 (±1)	>5 (±1)
P-3	0.15	ALOPE	VIS	1	1m (Line)	-	>2 (2)	Yes	-	-

VIS	Visible; 0.3 - 0.7 μm (Typical)
NIR	Near IR; 0.7 - 1.1 μm (Typical)
TIR	Thermal IR: 10.5 - 12.5 μm (Typical)
MW	L and S bands
-	No identified capability

Table 2. Satellite platforms, sensors, and oceanographic parameters.

Satellite and Sensor Characteristics						Oceanographic Parameter, Range (accuracy)				
							Chlorophyll a			
Satellite	Coverage Frequency	Sensor	Spectral Range	Spatial Resolution (at Nadir), m	Swath Width, km	Suspended Solids, mg/ℓ	Conc., mg/m^3	Diversity	Temperature Degrees K	Salinity ppt
Landsat	18 Day (9 Day for 2)	MSS	VIS,	70	185	>5 (±5)	"Bloom"(>10)	-	-	-
			TIR (*)	240	185	-	-	-	260-340(±1.5)	-
AEM-A	5 Day	HCMR	VIS, NIR	500	700	Yes (**)	-	-	-	-
			TIR	500	700	-	-	-	Yes (**)	-
Nimbus-7	6 Day	CZCS	VIS, NIR	800	1200	Yes (**)	Yes (**)	-	-	-
			TIR	800	1200	-	-	-	Yes (**)	-
SMS/GOES	30 min	VISSR	VIS	1000	3500	Qual.	-	-	-	-
			TIR	8000	3500	-	-	-	180-315(±2)	-
TIROS-N	0.5 Day	AVHRR	VIS, NIR	1000	2800	Qual.	-	-	-	-
			TIR	1000	2800	-	-	-	180-315(±1)	-

VIS - Visible; 0.3 - 0.7 μm (Typical)
NIR - Near IR: 0.7 - 1.1 μm (Typical)
TIR - Thermal IR; 10.5 - 12.5 μm (Typical)
* Landsat C only; one of two detectors operational
** Recent Launch, data being evaluated
- No identified capability

It is the purpose of this paper to review results from investigations that utilized remote sensing to locate features and/or measure parameter gradients in the coastal zone. Data collection, format, and computerized analysis techniques that use digital data from generally available instruments such as multispectral scanners (on aircraft and satellite platforms) will be discussed from a user's viewpoint. Much of this information also will be applicable to instruments under development such as passive microwave and active laser sensors.

EXPERIMENTS

Over the last several years, a number of experiments have been conducted in the United States coastal zone. Selected experiments and results will be described to illustrate remote sensing and surface data collection, data handling, analysis techniques, and products.

Remotely sensed data have been collected in conjunction with surface measurements over environmentally different areas of the coastal zone to study synoptic and temporal distributions of water quality parameters and to assess the applicability of remote sensors for monitoring the location and dispersion of river plumes. In this paper, emphasis will be placed on experiments that determined quantitative distributions of parameters usually associated with freshwater discharges (e.g., suspended solids, chlorophyll a, salinity, and thermal).

SYNOPTIC HIGH RESOLUTION OPTICAL RANGE AIRBORNE MEASUREMENTS

On June 23, 1977, the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) conducted a coordinated experiment to study synoptic thermal and oceanographic parameter distributions in the New York Bight Apex. Two unique aspects of this experiment were (1) concurrent surface water measurements made from a moving oceanographic research ship used to calibrate and interpret remotely sensed data collected from an aircraft platform, and (2) verbal communications used during the experiment to coordinate remotely sensed and surface measurements.

During the experiment, data were collected in the New Jersey nearshore waters from about Latitude 40°39' N on the north to Latitude 40°23' N on the south (Figure 1). One of the features monitored was the Hudson-Lower Bay estuarine plume which emanates from Sandy Hook Bay and flows southeast down the New Jersey shore (Johnson et al. 1980). The experimental locations were along ship tracks 1 and 2 and aircraft flight lines AC-1, AC-4, AC-5, and AC-7 (Figure 1). Remotely sensed data collections were made for a swath width of about 8,500 meters, centered on the above flight lines. Remotely sensed data were collected by a Modular Multispectral Scanner (M2S) and a Zeiss mapping camera onboard a NASA Johnson Space Center (JSC) C-130 aircraft from a nominal altitude of 3.0 kilometers (km) (10,000 Feet). The M2S has 11 bands in the visible, near infrared (IR), and thermal spectral ranges. Bandwidths and wavelengths of the remote sensors are shown in

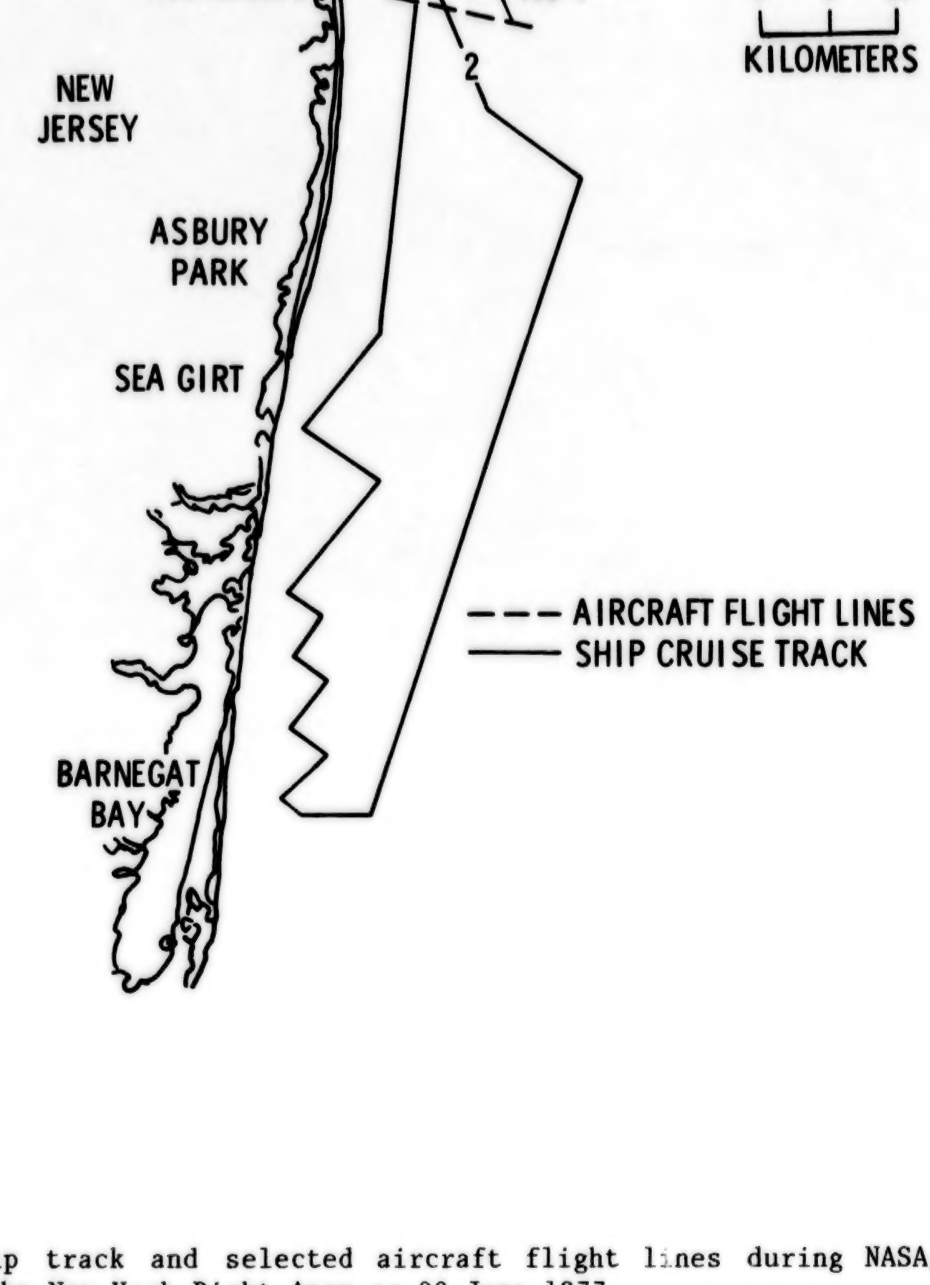

Figure 1. Ship track and selected aircraft flight lines during NASA/NOAA experiment in the New York Bight Apex on 23 June 1977.

Table 3, along with spatial coverage information at the flight altitude. Data collections were accomplished by multiple over-flights over the moving ship as it steamed along a track approximately south-southeast along the New Jersey shore, Figure 1. Data flights at about 20-minute intervals were planned so that overlapping remotely sensed data could be used to synoptically map features in the experimental area. Surface measurements made from the NOAA research ship Albatross IV were continuously recorded to determine chlorophyll a and suspended matter concentrations at the sampling depth of about 2 meters using a Turner flurometer and turbidometer, respectively.

Representative radiance values in the remotely sensed scene were used for qualitative analysis (e.g., for temperature distributions where no corresponding surface measurements were made) and quantitative analyses (e.g., using concurrent surface measurements). These radiances were determined by averaging over a 10 by 10 pixel field, then multiplied by instrument calibration values to determine sea surface temperature or radiances.

Photographic products (from the Zeiss mapping camera) and M2S thermal band (Band 11) radiances were used to locate features of primary interest in the remotely sensed scene. Evaluation of thermal data collected and instrument calibration indicated that sea surface temperature difference of 0.25°C could be detected. Comparison of the remotely sensed thermal distributions with the color aerial photography indicated a cold mass of upwelled water in the Bight Apex with an overflowing warm water plume that originated in the Sandy Hook Bay and flowed southeast into the Bight waters (Figure 2).

Further comparisons of the thermal map, photography, optical spectral range data, and shipboard measurements indicated a significant gradient where the research ship crossed the plume boundary at about 0930 EDT. Concurrent data collections were made by the aircraft (AC-7). This area indicated on the thermal mapping (Figure 2) was the focus of detailed quantitative analyses.

Observations for the quantitative analyses were determined from the continuously recorded (on strip chart) surface measurements of chlorophyll a and suspended matter at corresponding geographic locations of remotely sensed radiances. Multiple regression analyses were used to relate surface measurements of chlorophyll a and suspended matter (measured as turbidity) to normalized radiance measurements in the visible and near infrared (IR) spectral range (bands 1-10) of the M2S.

Regression equations for concentrations of chlorophyll a and suspended matter were:

$$\text{Chlorophyll } \underline{a} \text{ mg/m}^3 = 94.49 + 1419.6\, z_2 - 1499.5\, z_4$$

$$\text{Suspended matter, mg/l} = 33.19 - 166.65\, z_5$$

where z_i are normalized radiance differences for the M2S bands. Correlation coefficients between surface and remotely sensed measurements were 0.936 and 0.965 for chlorophyll a and suspended matter, respectively.

Table 3. Spectral and spatial characteristics of airborne remote sensors used on 23 June 1977 from an altitude of 3km.

I MODULAR MULTISPECTRAL SCANNER (M2S)

BAND	BANDWIDTH
1	380-440 nm
2	440-490 nm
3	495-535 nm
4	540-580 nm
5	580-620 nm
6	620-660 nm
7	660-700 nm
8	700-740 nm
9	760-860 nm
10	970-1060 nm
11	8000-13,000 nm
SCAN WIDTH m	8500
RESOLUTION m	9

II ZEISS MAPPING CAMERA

	SPECTRAL RANGE	FILM	RESOLUTION, m	FOOTPRINT, m
No. 1	400-700 nm	Color	0.4	4550 × 4550

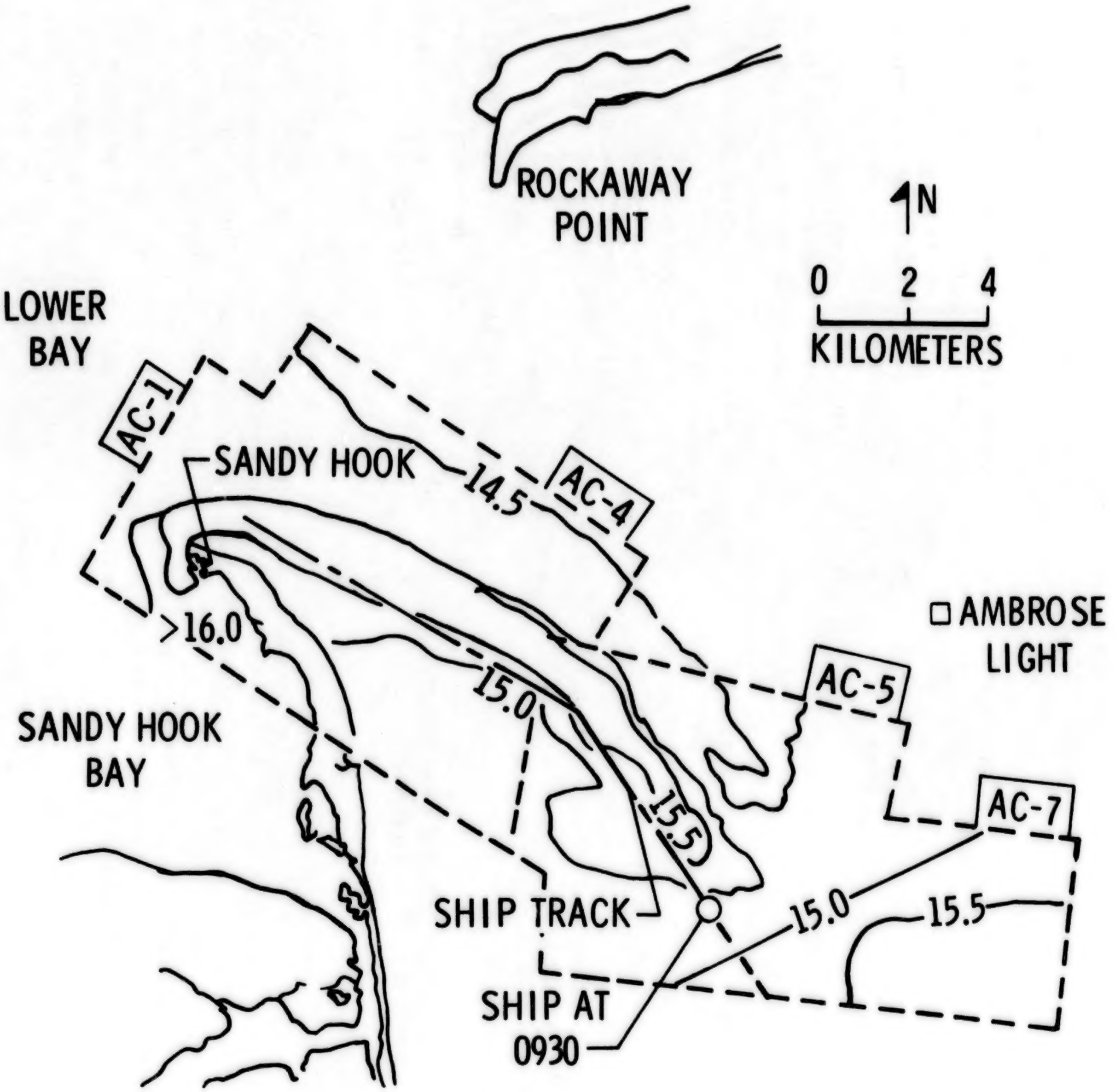

Figure 2. Thermal distributions from aircraft measurements of sea surface temperature (°C) in a selected part of the experiment area (ship track from about 0847 to 0940 EDT) on 23 June 1977. Measurements from the aircraft flight lines are labeled AC-1, AC-4, AC-5, and AC-7.

Comparison of the remotely sensed and measured values of chlorophyll a concentrations are shown on Figure 3. Distributions are approximately random above the fitted line, indicating the linear model is adequate for this set of data. Suspended matter analyses indicate similar characteristics. A correlation coefficient of 0.719 indicates relatively low covariance between concentrations of chlorophyll a and suspended matter (See Johnson 1978 for a discussion of covariance between parameters for other experiments).

Thermal variations (from aircraft calibrated data) and concentrations of chorophyll a and suspended matter (determined from the appropriate regression equations) are shown in Figure 4 along with surface observations for the selected part of the ship track. The estimated ship location at the time of aircraft overflight (AC-7) is also shown. The plume is readily distinquished from the surrounding oceanic waters by the individual and/or combined measurements.

Both temperature and suspended matter concentrations indicate small changes in the plume or surrounding oceanic water (e.g., from 0924 to 0929 in the plume and 0931 to 0935 in the oceanic water) while the chlorphyll a concentrations increase rapidly and somewhat erratically as the ship approaches the plume boundary (from 0924 to 0929). There are spikes in both chlorophyll a and suspended matter concentrations as the ship moves through the boundary (at about 0930) to the more uniform oceanic water.

Comparison of the thermal and concentration gradients along the ship's track suggest several interesting possibilities. First, the thermal distribution indicates relatively mild and uniform rates of mixing between the plume and oceanic water in the top meter of surface water; second, the erratic and rapid increase of chlorophyll a near the plume boundary and the spikes of chlorophyll a and suspended matter concentrations suggest small scale patchiness near the edge of the plume; third, on the oceanic water side of the plume there is a short mixing zone as evidenced by the gradual decrease beyond the spikes; and finally, the spatial displacement between the remotely sensed and shipboard measurements in the plume boundary indicates a sloping interface with depth between the plume and adjacent oceanic waters. Similar characteristics at plume/front interfaces in the Delaware Bay have been identified and reported by Klemas and Polis (1977).

Chlorophyll a distributions were determined using the regression equation over a portion of the area shown in Figure 2, specifically for the area covered by AC-7. (As noted earlier, this was for the period when the ship moved across the plume boundary). This chlorophyll a distribution is shown on Figure 5. As may be seen, the essential outline of the plume is indicated by chlorophyll a concentrations (Figure 5) as well as a thermal boundary (Figure 2) at the same location. Thus, the plume is characterized by having warm temperatures and high chlorophyll a concentrations. Outside of the plume, water had generally low chlorophyll a concentrations. However, we also may differentiate water outside the plume into two different temperature regions (Figure 2) which have similar chlorophyll a concentrations. The cooler water may be related to local upwelling and the warmer water is part of the normal surface water.

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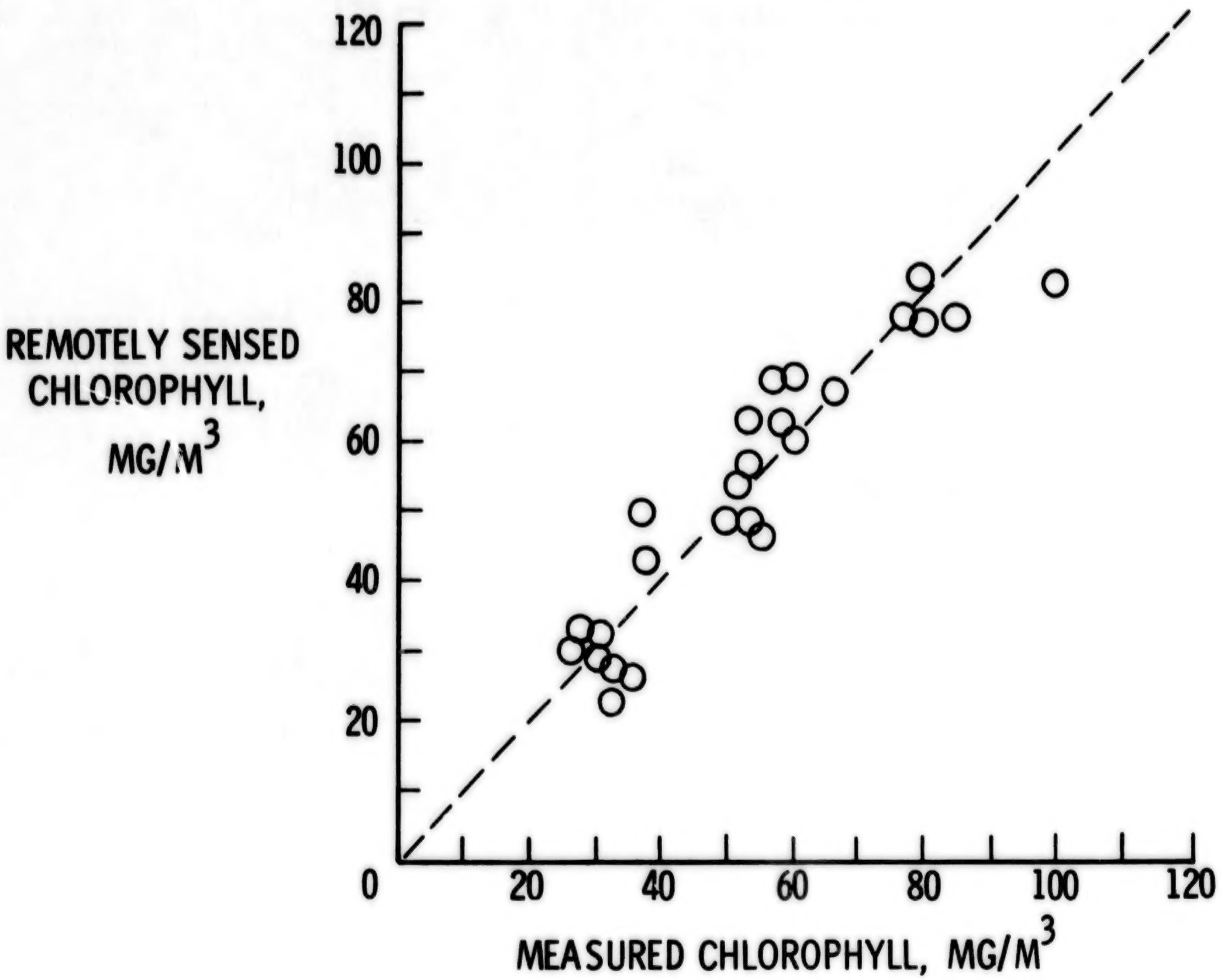

Figure 3. Comparison of remotely sensed and surface measured values of chlorophyll a from 0924 to 0934 EDT.

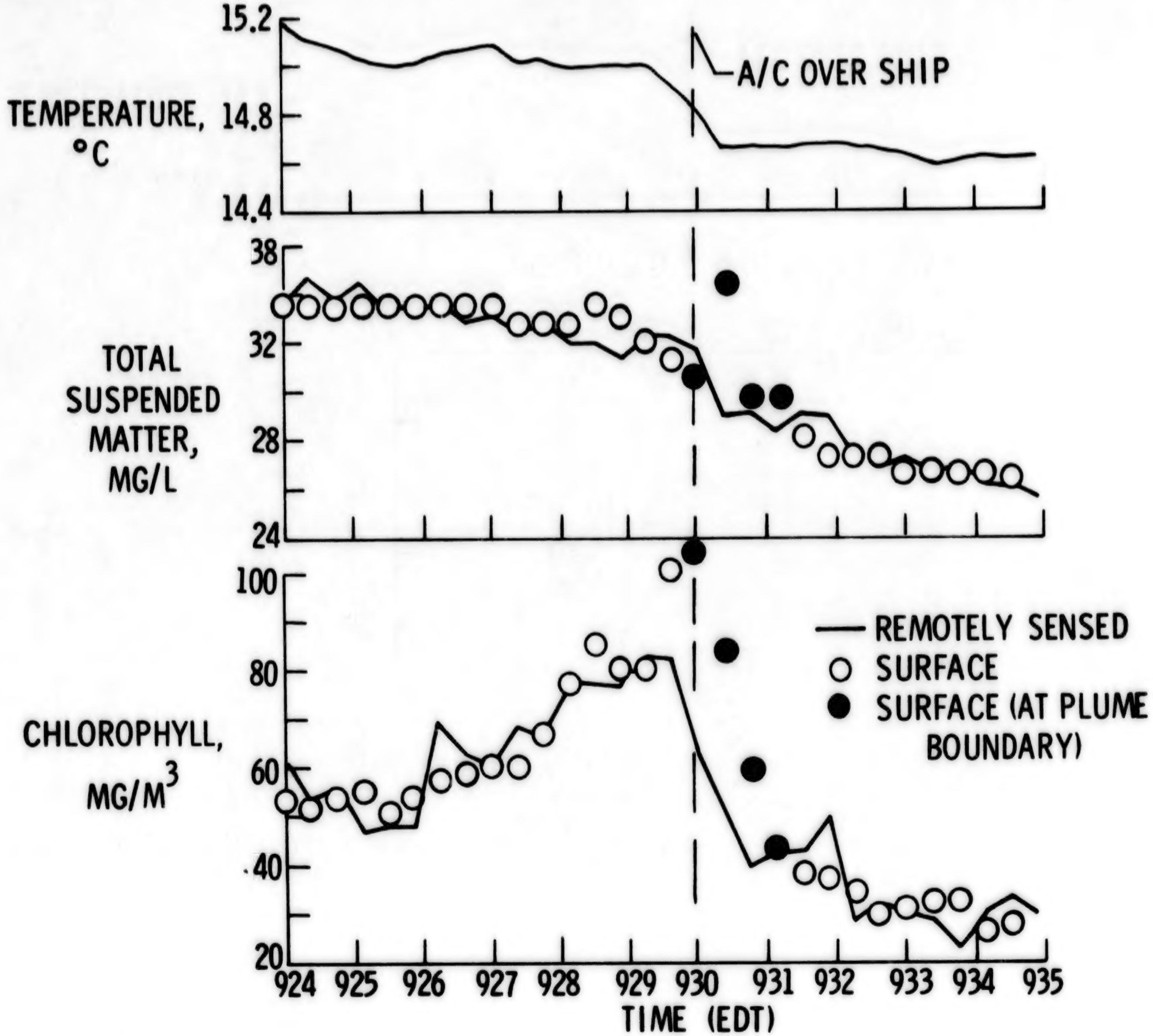

Figure 4. Comparison of sea surface temperature (°C) and concentrations of total suspended matter and chlorophyll a along part of the ship's track. Open circles are surface measurements used in regression analyses. Solid circles are surface measurements not used in regression analyses. Solid lines were determined from regression analyses (except tempertaure which used aircraft calibration values).

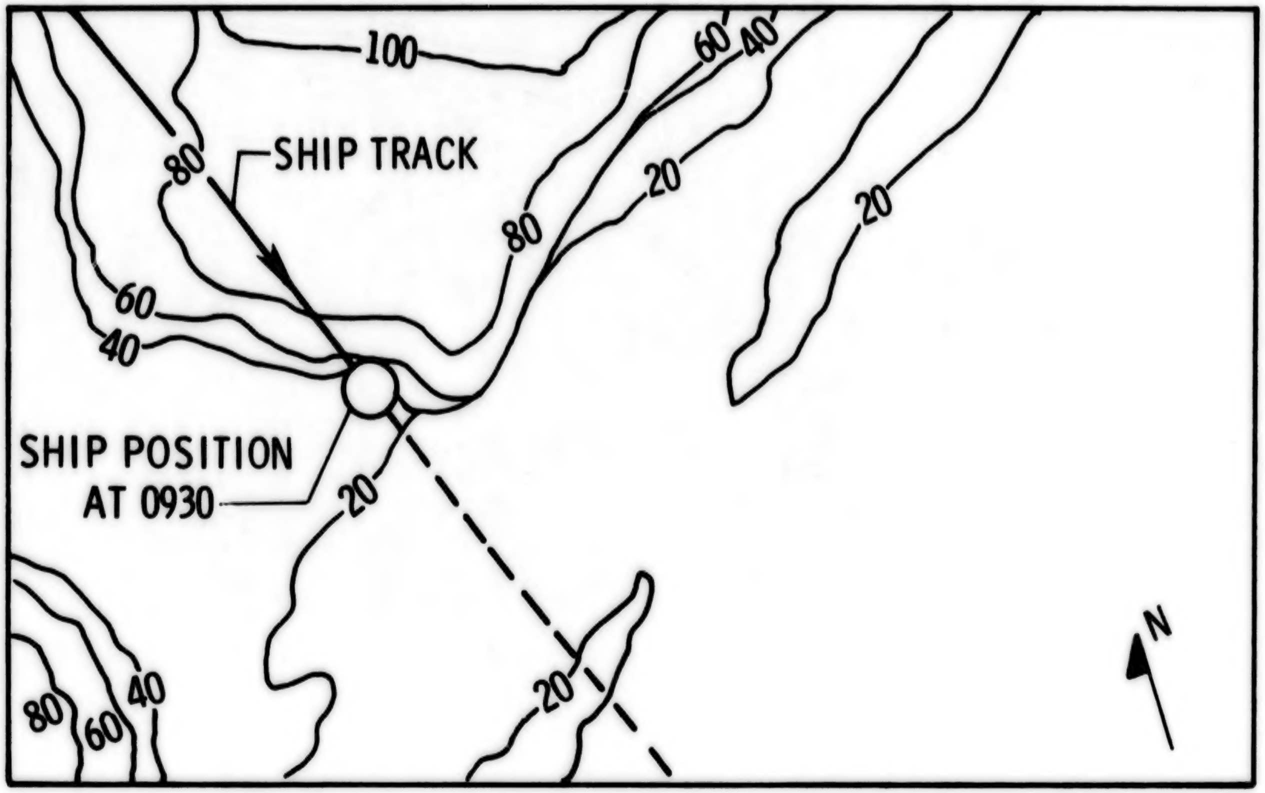

Figure 5. Quantitative chlorophyll a concentrations (mg/m^3) from remotely sensed data along flight line AC-7 (map compressed spatially along flight line - see figure 2). Ship track and position at 0930 are also shown.

PASSIVE MICROWAVE AIRBORNE MEASUREMENTS

Experiments have been conducted in the Chesapeake Bay, using passive microwave measurements to determine temperature and salinity distributions. A demonstration test flight in August 1976 of a microwave system, incorporating nadir viewing L and S band (1.43 and 2.65 GHz) radiometers by Blume et al. (1978) indicated that surface temperature can be measured to within 1°C and salinity with a mean deviation of 1 ppt for salinity greater than 5 ppt. To obtain these accuracies, the radiometers were calibrated before each flight and the radiometric data were corrected for extraterrestrial background radiation, atmospheric effects, sea surface roughness, and antenna beam efficiency. By flying a series of parallel east-west flight lines, a data grid was developed and used to plot surface isothermals (Figure 6) and isohalines (Figure 7) of the lower Chesapeake Bay and nearby ocean water. Comparison of these two figures and results from other experiments indicate the salinity map is more informative than the thermal map in the same areas.

During February 1978, microwave radiometer experiments were flown on a NASA C-54 aircraft around the island of Puerto Rico to detect submarine freshwater springs (Kendall 1980). Knowledge of the discharge characteristics and location of submarine freshwater spring outflows can enhance the determination of underground water sources for possible utilization as a freshwater supply. As the areas of these outflows exhibit surface temperatures and salinities which are different than the surrounding sea water, their detection by microwave radiometers is possible from a remote platform. Remotely sensed salinities in the flight path across Arecibo harbor and along the nearby coastline are shown on Figure 8. After separating the surface run-off contributions, such as rivers, lagoons marshes and bays, 44 submarine freshwater springs were identified which indicates that the submarine freshwater outflow locations are more numerous around the island than had earlier been estimated. The majority of the submarine springs are located at the northwest and southeast portion of the Puerto Rican coastline. Salinity and temperature distribution plots obtained along the flight path in longitude and latitude coordinates show that run-off direction can be determined. A comparison of outflow rate and remotely measured salinity and temperature gradients could lead to an interesting application of remote sensing for future submarine freshwater source surveillances.

During November 1979, NASA and the Skidaway Institute of Oceanography conducted a coordinated experiment to define the salinity distributions near rivers and sounds and major changes that occur from ebb to flood flow off the Georgia coast (Kendall 1980). On the afternoon of November 8, 1979, a series of 20 flight lines were flown by a NASA P-3 aircraft off the coast of Georgia for the purpose of measuring the salinity distribution with onboard microwave radiometers. The data were obtained from the middle portion of the ebb flow cycle to within one-half hour until slack ebb. The same timing was repeated for the flood flow cycle 18 hours later on November 9. The maps produced by the effort thus represent the salinity conditions of the water near the last half of the ebb and flood cycles. Sea-truth data for the overflight measurements were provided

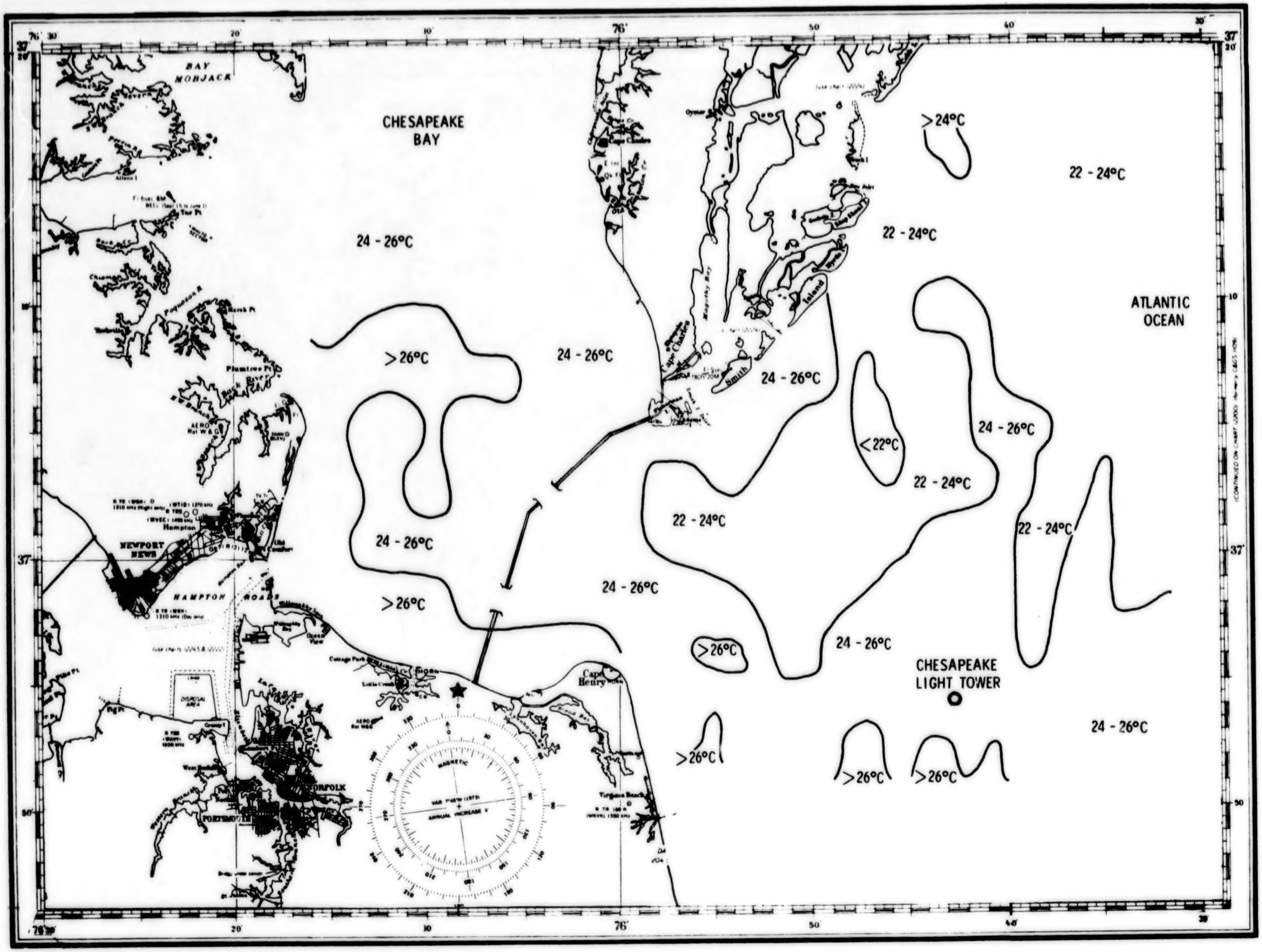

Figure 6. Isothermals of the lower Chesapeake Bay on 24 August 1976.

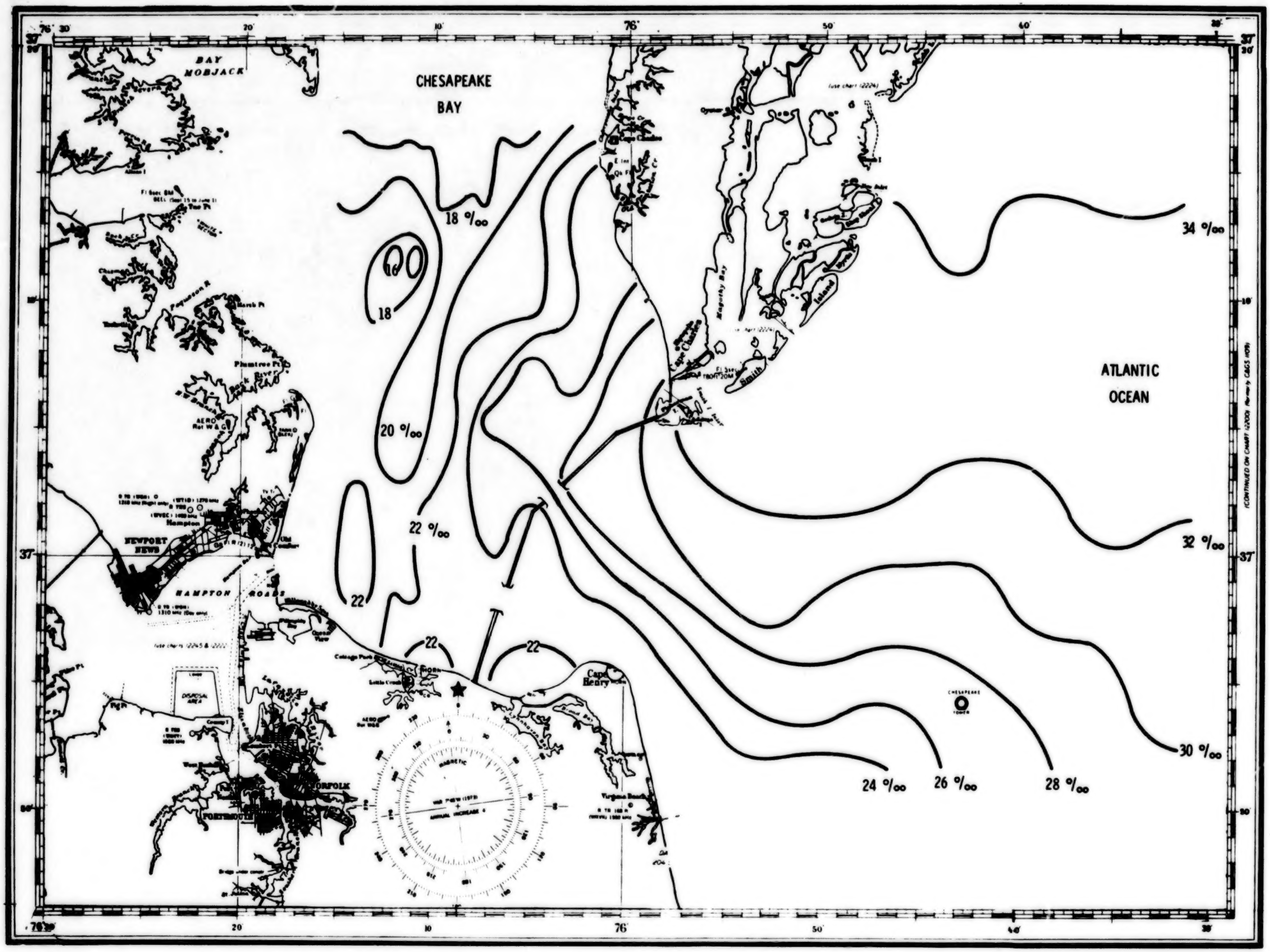

Figure 7. Isohalines of the lower Chesapeake Bay on 24 August 1976.

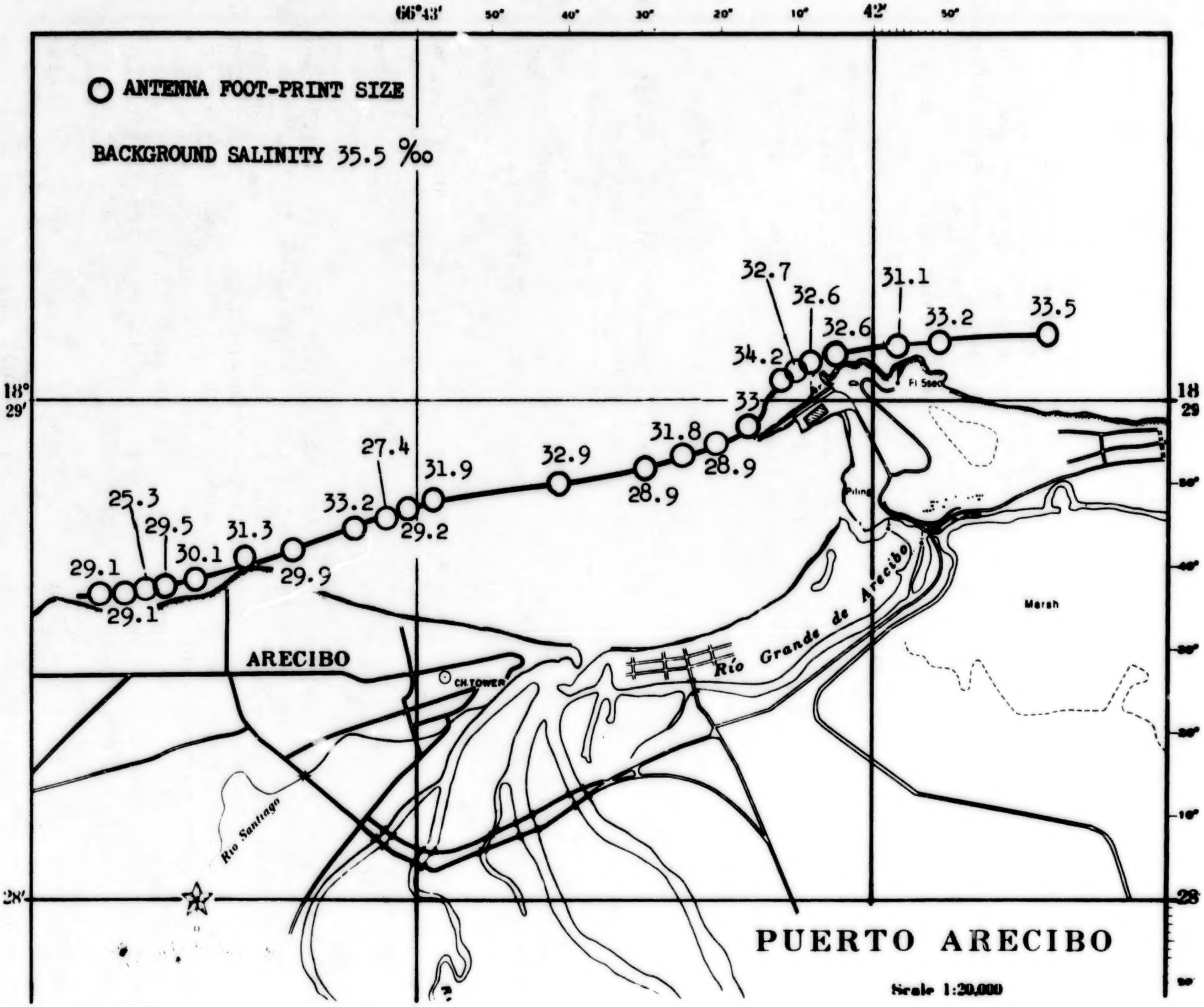

Figure 8. Salinity values along flight line across Arecibo Harbor and along nearby Puerto Rico coastline in February 1978.

by the R/V Kit Jones, R/V Blue Fin, and R/V Iselin. A comparison of measured salinities with corresponding sea-truth data shows that the salinity measurement was accurate to within 1.0 ppt. Preliminary results shown in Figure 9 indicate that the Savannah River plume dominated the salinity regime and extended out from the Savannah River mouth about 12 km during ebb tidal conditions. The plume merged into a band of low salinity water extending along the Georgia-South Carolina coast which was produced by the many river sources of fresh water entering the coastal waters. The principal value of this survey was to help define the role of ocean currents over scales smaller than the plume dimensions. Such knowledge would enable us to relate the distribution of fresh water in river plumes to tidal and wind-driven currents that vary with local bottom bathymetry near the inlet mouth.

ACTIVE LASER AIRBORNE MEASUREMENTS

An Airborne Lidar Oceanographic Probing Experiment (ALOPE) system has been developed and laboratory tested (Brown et al. 1978). The laser in the system is a unique four-color dye laser pumped by a single linear xenon lamp. Fluorescent dyes, which lase at 454, 539, 598, and 617 nm, are the active medium for the separate dye lasers, which are separately activated using a rotating intercavity shutter. Induced fluorescence from chlorophyll a in the water is collected by a telescope, passed through a narrow band pass filter (centered at 685 nm), digitized, and recorded. Results of laboratory tests using mixtures of species (from each of four color groups: blue-green, golden brown, green, and red) indicated correlation coefficients (between samples and ALOPE measurements) of 0.994 for total chlorophyll a and from 0.81 to 0.88 for the individual color groups.

Results from a NASA/University of Rhode Island/EPA Narragansett Bay Experiment suggest the applicability of the ALOPE system for monitoring total chlorophyll a and phytoplankton diversity in estuarine systems (Farmer et al. 1980). In this Narragansett Bay experiment, the instrument was mounted on a helicopter platform (nominal flight altitude 30 meters). The system is currently being evaluated from an aircraft platform which increases coverage and coordination with other instruments. Surface measurements required for calibration of the remotely sensed data include in situ water attenuation coefficients.

ENVIRONMENTAL SATELLITES

Multispectral data collected over estuarine and coastal zones from Landsat environmental satellites have been evaluated to study water quality and pollution features, such as suspended solids, chlorophyll a, and plumes resulting from ocean dumps. Using suspended solids as a tracer, Klemas et al. (1974) studied current flow and plumes in the Delaware Bay and nearby coastal areas.

Bowker and Witte (1977) and Bowker et al. (1975) investigated the utility of repetitive Landsat coverage for monitoring changes in the lower Chesapeake Bay. Recently, Bowker (1980) of the NASA Langley Research Center developed a mosaic of Landsat imagery that shows features associated with nearshore regions of the gulf coast (Figure 10).

Landsat digital data are available on Computer Comparable Tapes (CCTs) through the EROS Data Center.

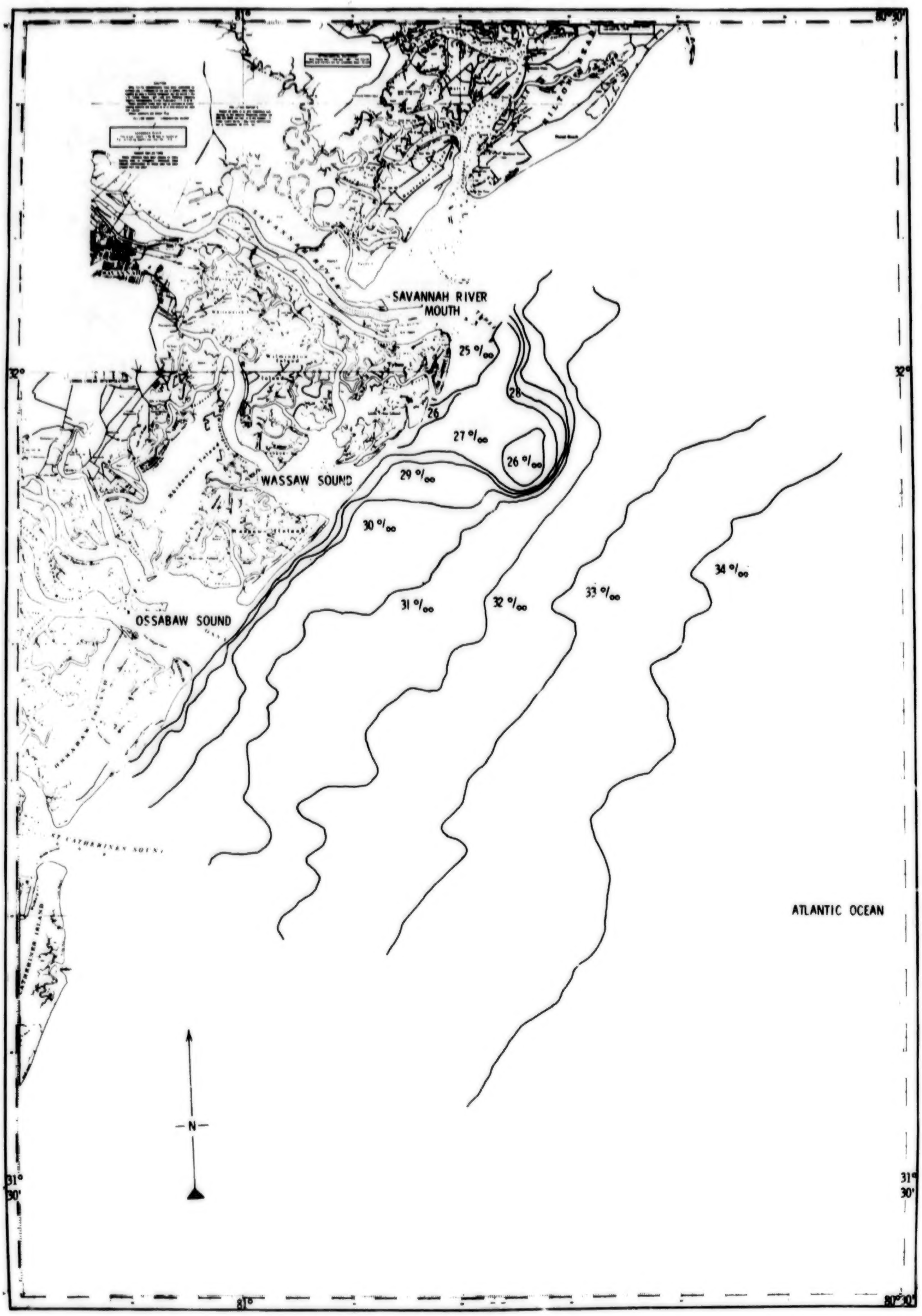

Figure 9. Salinity map of Georgia coastal area during ebb tidal cycle on 8 November 1979.

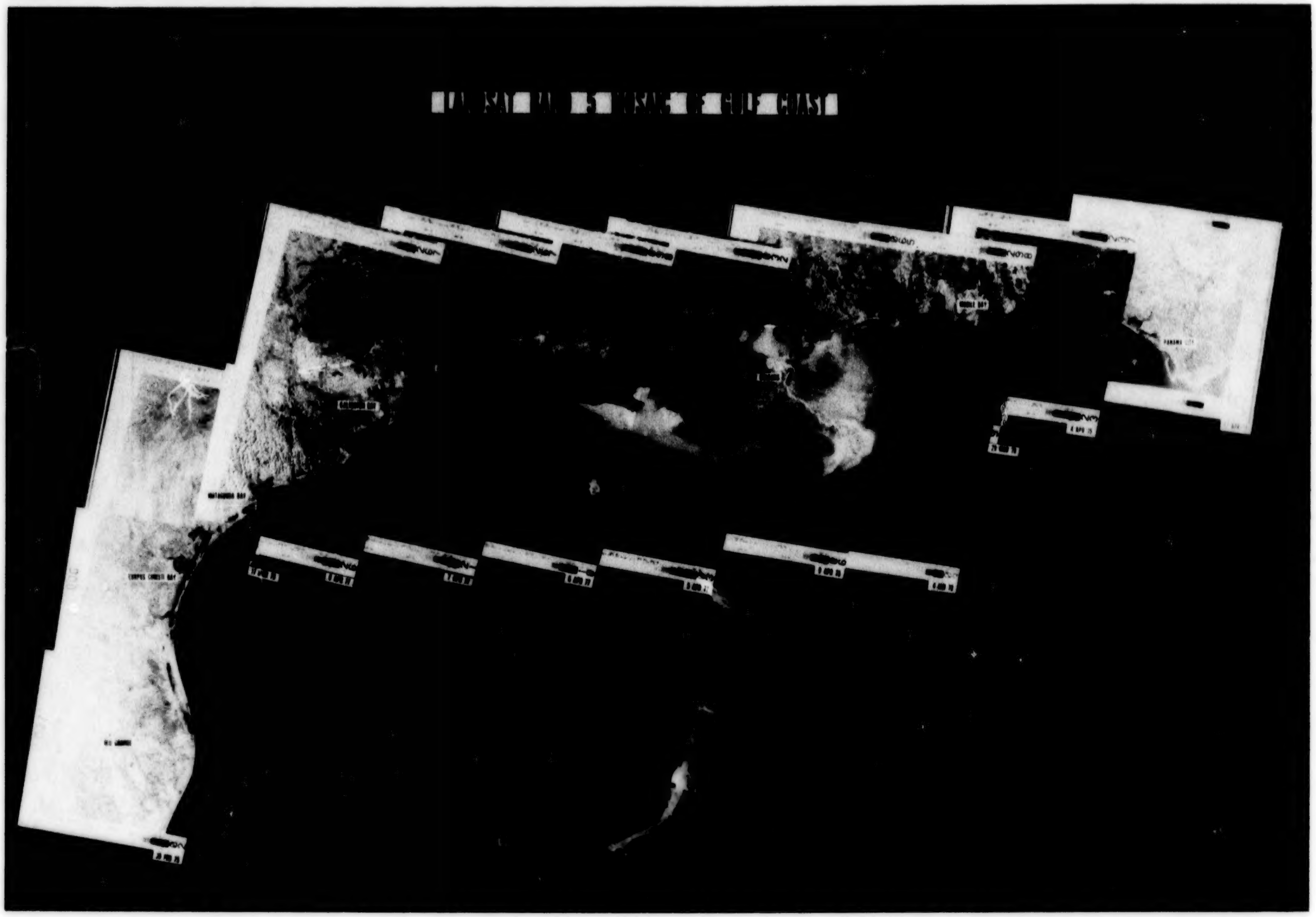

Figure 10. Mosaic of Landsat imagery showing dominant oceanographic features along the Gulf of Mexico shoreline.

The format (typically nine-track, 800 bytes per inch [bpi] is essentially the same as for the airborne M2S data and many of the preprocessing and analysis techniques described earlier also apply.

CONCLUDING REMARKS

Results of experiments conducted in the United States coastal zone indicate that remote sensing may provide data and measurements of interest to oceanographers and environmental managers. High resolution airborne sensors may be utilized to provide information on oceanographic parameters such as particulates, salinity, temperature, chlorophyll a, and possibly phytoplankton diversity. Repetitive data collections from environmental satellites provide synoptic and temporal information on high radiance contrast features such as river plumes.

Airborne optical spectral range sensors (e.g., multispectral scanners and cameras) measure reflected radiation in several spectral bands. Parameters that have indicated radiance changes are temperature and concentration changes of chlorophyll a and suspended solids. Quantitative analysis techniques, using multiple regression, have been developed to relate sea-truth measurements to corresponding remotely sensed data. Results of these analyses--calibrated regression equations--have been used to map distributions of parameters such as chlorophyll a and suspended solids.

Qualitative analyses use photo analysis or other techniques in which the interpretations do not require concurrent sea-truth measurements. In general, features of interest, such as a river plume or a plume from ocean dumping of waste materials have radiance or temperature levels different from surrounding water. The extent of the feature may be mapped using equal radiance mapping and/or classification techniques. An environmental application of these techniques is the monitoring of plume flows from estuarine systems.

Microwave spectral range measurements provide information on temperature and salinity of surface waters. Synoptic coverage from parallel aircraft flight lines provides data for mapping distributions of these parameters to describe features such as river plumes and locations of submarine freshwater springs. Microwave measurements may be made over a wide range of environmental conditions.

Airborne active laser remote sensors such as the ALOPE may be used to determine total chlorophyll a density and to estimate phytoplankton diversity. Laboratory results have indicated statistically significant correlations between the remotely sensed and the measured densities and diversity. Preliminary evaluations of data from a field test in the Narragansett Bay support results obtained in the laboratory. As and active system, the ALOPE is not limited to daylight operations, as are passive optical spectral range sensors. At the present time, in situ attenuation coefficient measurements are required.

Repetitive remotely sensed measurements from environmental satellites provide wide area synoptic measurements on features that exhibit high radiance contrast. Proposed environmental and meteorological satellites will provide improved spectral and spatial resolution as well as increased coverage frequency.

Presently, the primary applications for optical range satellite based remote sensors appear to be for wide area and/or repetitive measurements of well defined features such as sediment plumes and spectrally different ocean water masses.

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DISCUSSION

Question: Tom Frazier, You mentioned one limitation. I'm wondering if you have any limitation dealing with water that is highly colored such as a hundred to two hundred cobalt platinum units. Will this foul up any of your estimations such as chlorophyll or salinity?

Answer: There has to be something in the water that gives the color. If it's a dissolved organic material, then that would have the effect of limiting the penetration. On the other hand, if what you're looking at is largely surface phenomenon, then that would merely change the background. So, I don't think I have a direct answer for that, it depends on the particular circumstances. And really it depends on how much contrast you have. It's the same old thing if you're looking for a gray target, against a gray background, you're going to have trouble finding it. On the other hand, if you're looking for a black target or something that has different radiance characteristics from the background, then you can find it relatively easily. So I think without knowing what the material is, it is very difficult to answer the question.

CONCENTRATION, EXTENT, AND DURATION OF SALINITY INTRUSION INTO THE COLUMBIA RIVER ESTUARY

SEPTEMBER-OCTOBER, 1977-1978

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Joseph T. Durkin and Theodore H. Blahm

National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northwest and Alaska Fisheries Center
Coastal Zone and Estuarine Studies Division

ABSTRACT

Eight 24-hour (h) surveys were conducted during September and October 1977 and 1978 to record the extent, concentration, and duration of salinity intrusions into the Columbia River estuary. Monitoring stations were established at Tongue Point, Harrington Point, Grays Point, and in the north channel of Cathlamet Bay. The objective was to simultaneously measure salinity during maximum (spring) and minimum (neap) tidal cycles.

Monthly neap tides produced the highest concentrations with the longest durations and farthest upstream intrusions of saline waters. Salinities reached 30 parts per thousand (ppt) at Tongue Point and 17 ppt at Harrington Point. Concentrations of salt water exceeding 11 ppt were measured continually throughout one 24-h survey (7 to 8 September 1977) at Tongue and Grays Points. The farthest upstream intrusion of salt water 2 ppt was recorded between Buoy 14 and 14A at Columbia River Mile (RM) 26.5.

INTRODUCTION

In 1977 three events occurred which necessitated the gathering of up-to-date information on the intrusion of salinity into the Columbia River estuary: (1) near record low flows for the Columbia River were predicted for the summer/fall of 1977; (2) the Corps of Engineers (COE) dredged approximately 6.9 million m^3 of sediment from the Columbia River bar during the spring and summer of 1977 (this increased the depth of the bar from 14.6 to 16m); and (3) on-site salinity studies were needed to verify the Columbia River physical model which was recently renovated for studies at the COE Waterways Experiment Station (WES).

This study was partially funded by the Portland District COE and was conducted by the National Marine Fisheries Service (NMFS), Coastal Zone and Estuarine Studies Division (CZES), Northwest and Alaska Fisheries Center. The objective was to determine the concentration, extent, and duration of salinity intrusion into the Columbia River estuary during a period of low river flow, September and October, 1977. In addition, NMFS conducted a similar study in September and October of 1978 to obtain data for comparison with the data from the 1977 low-flow year.

STUDY PLAN AND METHODOLOGY
(METHODS AND MATERIALS)

In August 1971 preliminary studies were conducted to locate appropriate stations close to or on the main ship channel where vessels could anchor and not obstruct river traffic. Also, samples were taken at various depths at locations north and south of the main ship channel to determine if salinity intrusions reached levels justifying documentation during the 24-h surveys to follow. Boats were anchored at predetermined points until high tide or peak salinities occurred, then moved upriver following the 2 ppt salinity level or downstream if salinities did not reach 2 ppt.

Stations selected for the 24-h salinity surveys are shown in Figure 1. Station 1 (Tongue Point) and Station 4 (Harrington Point) were located near the main ship channel. Station 2 was located near Grays Point on the Washington side of the river; whereas, Station 3 was on the Oregon side in Cathlamet Bay. River miles and the position of navigation buoys referred to in the text are also shown in Figure 1.

Salinity, conductivity, and temperature were measured at least once per hour (on the hour) at each meter of depth during eight 24-h survey periods at the four locations.

Measurements were taken with Beckman (Model #RS5-3) salinometers (reference to trade names does not imply endorsement by NMFS) values were recorded to the nearest tenth. River distances are presented in statute miles and tide elevations in feet to correspond to common usage on navigation and tide charts.

The four vessels were anchored on station and remained there for approximately a 24-h period. Some surveys were shortened because saline water had receded and the tide was ebbing. A roving boat was used to locate the furthest extent of saltwater intrusion (2.0) ppt during each survey. Because of safety and the difficulty in locating position markers at night, the roving boat operated only during daylight.

Sampling periods were selected to correspond to the monthly spring and neap tidal cycles in September and October of 1977 and 1978. Spring tides are tides of increased range occurring during the times of a new and full moon; these rise higher and fall lower than during the rest of the month. Neap tides are tides of decreased range occurring during times of the first and last quarters; these tides do not rise as high or fall as low as tides during the rest of the month.

River flows were determined using the daily mean flow at Bonneville Dam, the Willamette River at Portland, and the Cowlitz River at Castle Rock. River flows presented for the 24-h survey periods were calculated by taking the average flow during a 7-day period (the first day

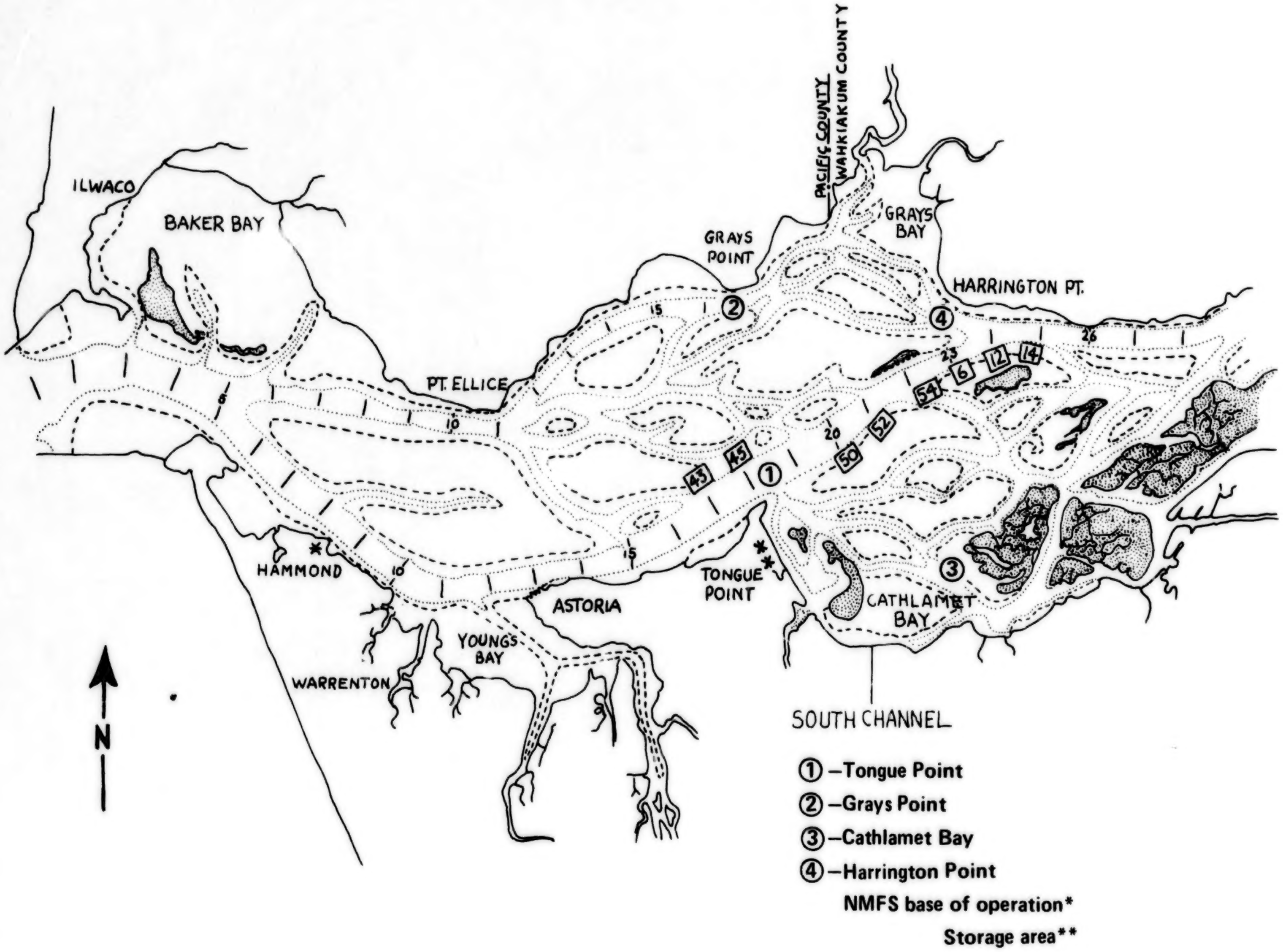


Figure 1. Sampling stations in the Columbia River estuary for the 1977-1978 salinity surveys. Distances (in river miles) are located in the center of the channels. Pertinent navigation markers are indicated by numbered squares.

of the sampling period plus the six previous days). Tide data were obtained from the National Ocean Survey NOAA and are for the Tongue Point tide station. Columbia River tide data are presented in relation to mean lower-low water.

RESULTS AND DISCUSSION

24-HOUR SURVEYS, 1977

7 and 8 September

The first 24-h survey was during a neap tide cycle with a maximum tidal range of 6.8 feet. Average river flow was 3,114 m^3/s (111,000 cfs) or 88 percent of the 15-yr average for this period. These conditions produced a substantial saline intrusion into the estuary not only in the navigation channel, but also in the side channels. Maximum upstream intrusion (3.1 ppt was found at Buoy 12, which is approximately RM 25. Salinities exceeding 15 ppt remained throughout the 24-h period at Tongue Point. Measurements were taken from the roving boat off Woody Island Channel and from Harrington Point to Grays Point; salinity was found in both areas. Water temperatures ranged from 20°C (river) to 14°C (brackish). Hourly salinity concentrations measured at our sampling stations are shown in Figure 2.

17 and 18 September

The second survey was during a spring tide cycle with a tidal range of 9.5 feet. The high-high tide intrusion did not result in salinities that exceed 10.6 ppt at any of the four monitoring stations (Figure 2). River flows averaged 3,270 m^3/s (115,500 cfs) and were approximately normal for this time of year. Water temperatures ranged from 19°C (fresh) to 16°C (brackish). A peak salinity intrusion of 2.6 ppt was measured at Buoy 54 (RM 22) at 1740 H.

5 and 6 October

The third survey was conducted on a neap tide cycle with a maximum range of 5.8 feet; river flows averaged 3,665 m^3 (129,500 cfs). Peak concentrations of salt water recorded during the study occurred at all four stations during this survey. Salinity was present at all but the Harrington Point site throughout this survey (Figure 2). Water temperatures ranged from 11° to 16°C. Salinities of 8.7 ppt were measured at 2100 h on 5 October between Buoy 14 and 14A (RM 26.5) in the main ship channel. This was the highest concentration of salt water to intrude this distance during any of the eight surveys.

13 and 14 October

The fourth survey (13 to 14 October) was selected to monitor a 10-ft tidal change. On 13 October a high-high tide of 8.8 feet occurred at 1318 h, and a low-low tide of -1.3 feet occurred at 2012 h. Severe tidal currents occurred during ebb flow. River flow during this survey averaged 3,420 m^3/s (120,000 cfs). Salinity intrusions corresponding with the high-high tide (8.8 feet) were recorded at Tongue Point, and in Cathlamet Bay (Figure 2). Salinity was recorded only at Tongue Point and Grays Point during the (7.5 foot) low-high tide on 14 October. Salinities did not exceed 10.0 ppt at any

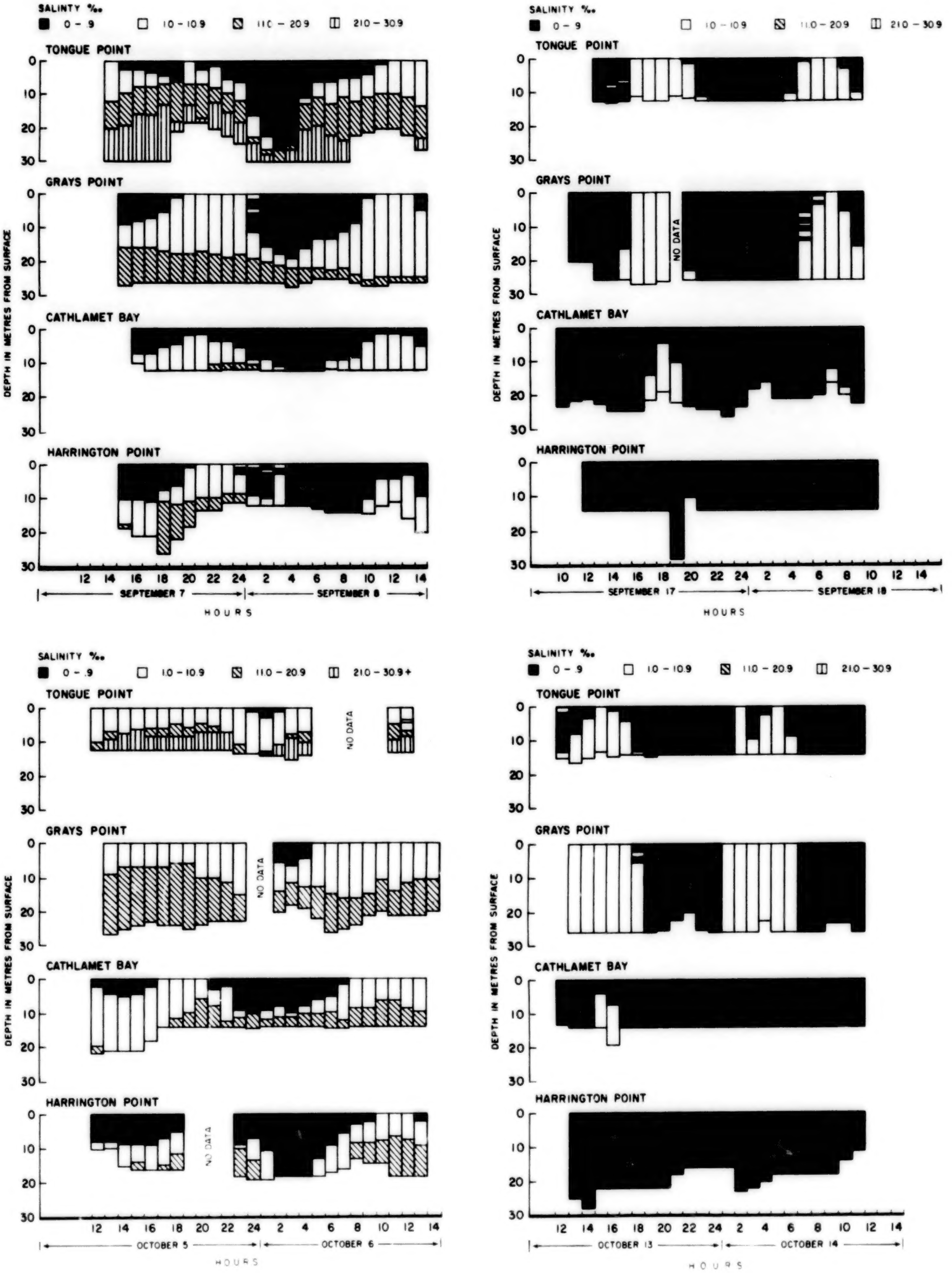


Figure 2. Salinity recorded during 1977 surveys at four locations in the Columbia River estuary.

station during this survey. Water temperatures ranged from 12° to 15°C. A salinity intrusion of 2.1 ppt reached Buoy 54 (RM 21.8) at 1600 h.

24-HOUR SURVEYS, 1978

The objective of the 1978 salinity surveys was to obtain salinity information during a normal flow year for comparison with the data collected in the low flow year of 1977. Mean daily flow into the Columbia River estuary in September 1977 was approximately 3,318 m^3/s (117,000 cfs) as compared to 4,780 m^3/s (169,000 cfs) in September 1978. October 1977 flows averaged 3,362 m^3/s (119,000 cfs) as compared to 4,379 m^3/s (155,000 cfs) in October 1978.

18 and 19 September

The fifth survey was conducted on 18 and 19 September during a spring tidal cycle. Maximum tidal range was 9.2 feet with a high-high tide of 8.4 feet at 1430 h and the low-low tide (-0.8 feet) at 2100 h. Average river flow during this period was 5,159 m^3/s (182,200 cfs). The highest concentration of salinity measured at the four monitoring stations (4.9 ppt) occurred off Grays Point at 1630 h. Salinity concentrations did not exceed 0.9 ppt in Cathlamet Bay or at Harrington Point (Figure 3). Water temperatures ranged from 18°C (fresh) to 16°C (brackish). The furthest point of salt water intrusion (2.8 ppt) recorded was southwest of Rice Island (RM 20.4 at 1520 h.

25 and 26 September

The sixth survey took place during the September neap tide cycle, with a maximum tide of 6.1 feet. The high-high tide at Tongue Point was 6.8 feet at 2000 h followed 7 h later with a low-low tide of 0.7 feet. Average daily river flow for the period was 5,005 m^3/s (176,000 cfs). Salinities greater than 2.9 ppt were present near the bottom at Tongue Point, Grays Point, and in Cathlamet Bay throughout the 24-h survey (Figure 3). Measurements were taken from the roving boat throughout the upper estuary. A maximum upstream intrusion (3.7 ppt) was recorded at 1300 h on 26 September at Buoy 12) (RM 24.9). Water temperatures ranged from 15.3° C (brackish) to 17.4°C (fresh).

16 and 17 October

Survey seven was conducted on 16 and 17 October during the spring tidal cycle. Highest tide of the month was recorded at Tongue Point on 16 October at 1312 h. The high-high tide (8.8 feet) was followed by a low-low tide of -1.1 feet; a differential of 9.9 feet. River flows averaged 4,346 m^3/s (153,000 cfs). Salinities did not exceed 9.2 ppt at any of the four monitoring stations (Figure 3). Water temperatures ranged from 16.2°C to 14.6°C. A peak salinity intrusion of 3.7 ppt was recorded at 1500 h in the main ship channel near Buoy 54 (RM 21.8).

24 and 25 October

The eighth 24-h survey took place during a neap tide cycle on 24 and 25 October. Maximum tidal range during this survey was 5.6 feet. Average river flow was 4,480 m^3/s

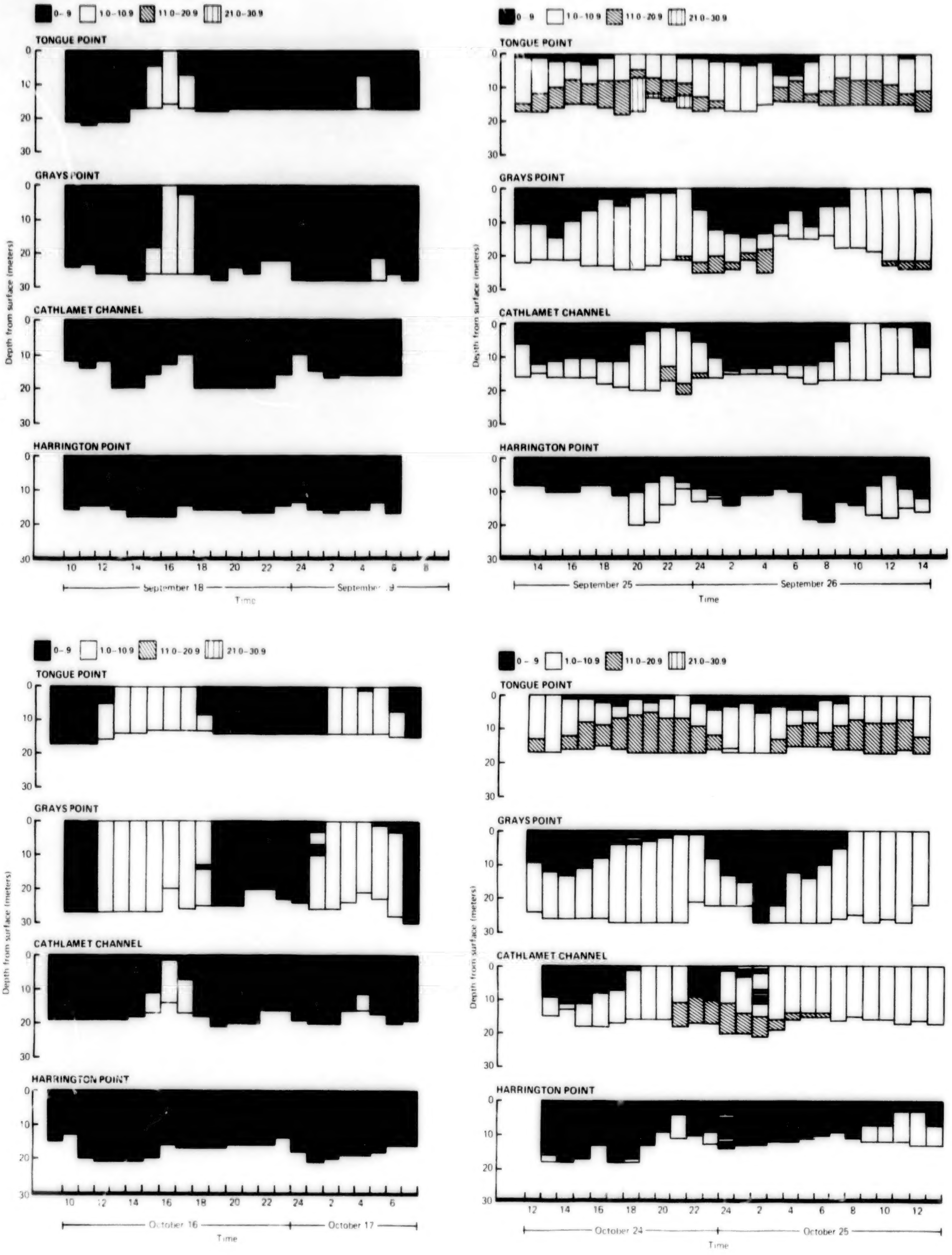


Figure 3. Salinity recorded during 1978 surveys at four locations in the Columbia River estuary.

(158,000 cfs). A substantial salinity intrusion occurred throughout the estuary (Figure 3), with a maximum upstream intrusion of 4.2 ppt recorded at Buoy 13 (RM 25.9) at 2230 h on 24 October. Water temperatures ranged from 11.5° to 15.1°C.

SUMMARY AND CONCLUSIONS

Salinity, conductivity, and temperature were measured hourly at each meter of depth at four locations in the Columbia River estuary during eight 24-h surveys. The extent of the saltwater intrusion was determined for each survey by following the saltwater wedge as it moved upstream.

The 1977 salinity studies took place during a near record lowflow period for the Columbia River. Mean monthly flows into the estuary during September and October of 1977 were 77 and 70 percent of the 15-yr average. River flows during September and October 1978 were near normal at 117 and 100 percent of the 15-yr average, thus providing data for comparison.

Our sampling periods for the 1977 and 1978 surveys were selected to correspond to the September and October monthly spring and neap tide cycles. Average river flow during the four 24-h salinity surveys in 1977 ranged from 3,114 m^3/s (110,000 cfs) to 3,665 m^3/s (129,000 cfs). Salinity data were collected over tidal ranges which varied from a minimum of 3.4 feet to a maximum of 10.1 feet. Figure 4 shows the 24-h tide cycles and corresponding salinities at Tongue Point for the 1977 surveys.

River flows during the 1978 salinity surveys ranged from 4,346 m^3/s 153,500 cfs) to 4,149 m^3/s (182,000 cfs). Maximum tidal range during the 1978 surveys was 9.9 feet on 16 October, a minimum tidal range of 2.9 feet was monitored on 24 October 1978. The tide cycles and corresponding salinities at Tongue Point are presented in Figure 5.

Extent of upstream intrusion of salinity was recorded for each survey; the criterion established was the farthest intrusion of salinity 2.0 ppt. Salinity intrusion in the main ship channel extended at least 20 miles upstream during all eight surveys (Table 1).

Monthly neap tides produced the highest salinity concentrations with the longest duration and the farthest upstream intrusion of saline water. The higher river flow during the 1978 surveys did restrict the concentration and extent of intruding salt water; however, during the 24 October 1978 survey, saline water (4.2 ppt) was measured at RM 25.4 during a mean flow period of 4,480 m^3/s (158,220 cfs).

The highest concentration of salt water (34.2 ppt) measured was at Tongue Point on 5 October 1977. This concentration surpassed all known documented records. In addition, salinity near the bottom (12 to 13 m remained above 20 ppt during the first 11 h of the survey.

Maximum concentration of salinity recorded at the Gray Point site (RM 19.3) was 17.1 ppt during the

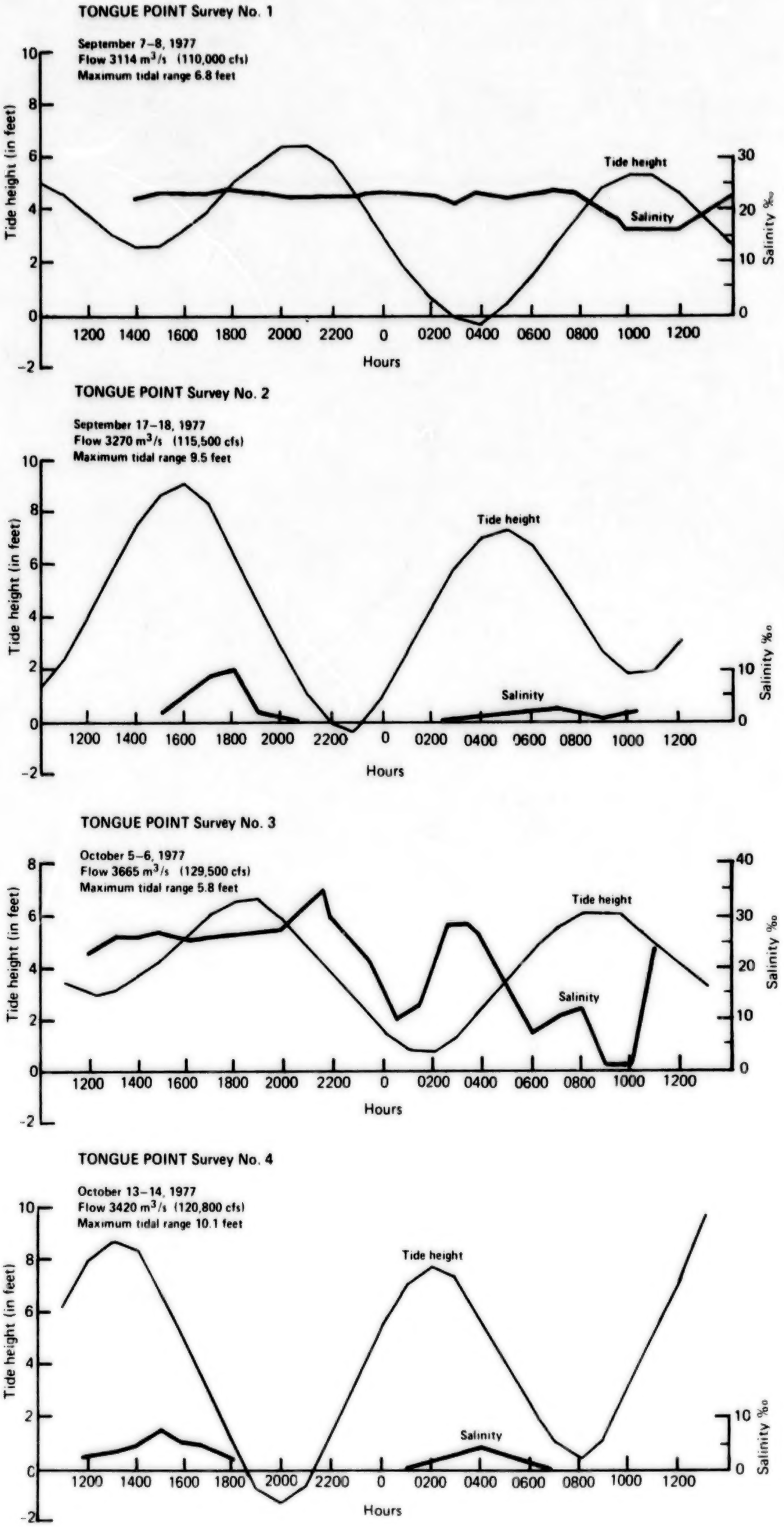
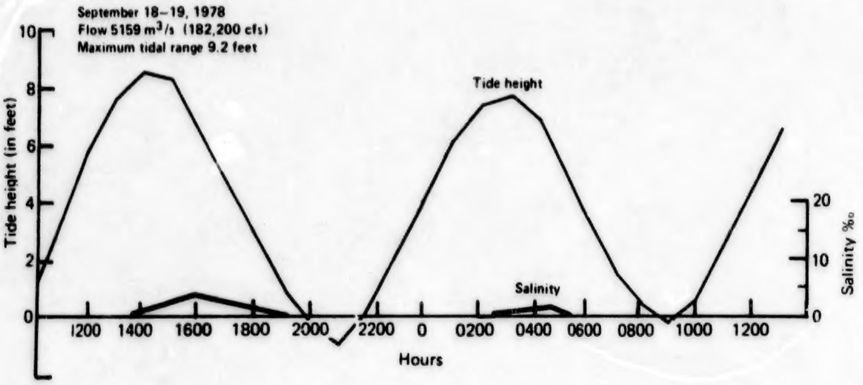
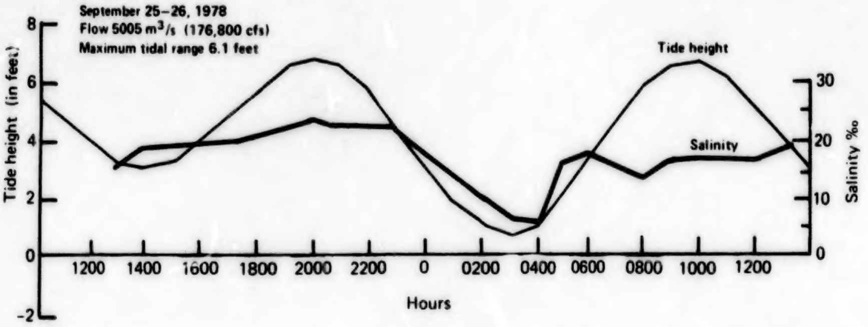


Figure 4. Twenty-four hour tide cycles and corresponding salinities at Tongue Point (RM 18.3) during the four 1977 surveys.

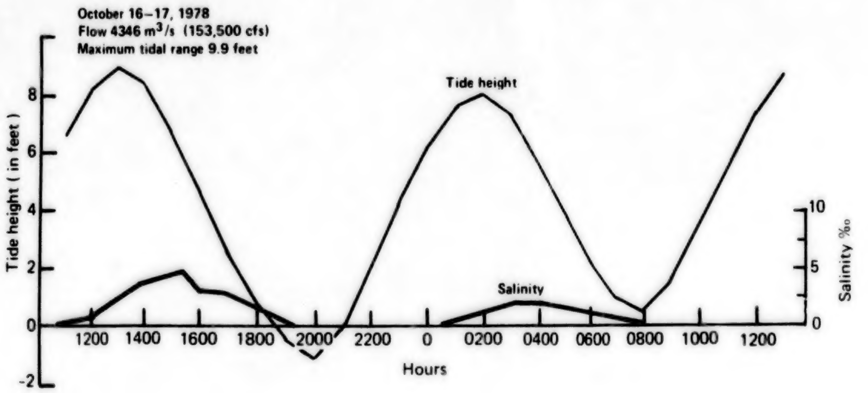
TONGUE POINT Survey No. 5


September 18–19, 1978
Flow 5159 m³/s (182,200 cfs)
Maximum tidal range 9.2 feet

TONGUE POINT Survey No. 6


September 25–26, 1978
Flow 5005 m³/s (176,800 cfs)
Maximum tidal range 6.1 feet

TONGUE POINT Survey No. 7


October 16–17, 1978
Flow 4346 m³/s (153,500 cfs)
Maximum tidal range 9.9 feet

TONGUE POINT Survey No. 8

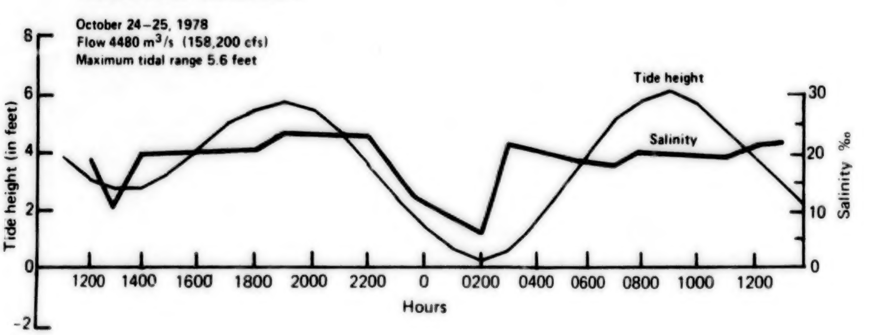

October 24–25, 1978
Flow 4480 m³/s (158,200 cfs)
Maximum tidal range 5.6 feet

Figure 5. Twenty-four hour tide cycles and corresponding salinities at Tongue Point (RM 18.3) during the four 1978 surveys.

Table 1. Maximum extent of saltwater intrusion of> 2.0 o/oo during eight 24-h surveys in the Columbia River estuary September and October 1977-1978.

Date	Flow		Maximum tidal range (feet)	Distance of intrusion (miles)	Salinity recorded (o/oo)
	(m^3/s)	(cfs)			
			1977		
7 Sept.	3,114	109,983	6.8	25.0	3.1
17 Sept.	3,270	115,484	9.5	22.0	2.6
5 Oct.	3,665	129,454	5.8	26.5	8.7
13 Oct.	3,420	120,774	10.1	21.8	2.1
			1978		
18 Sept.	5,159	182,194	9.2	20.4	2.1
26 Sept.	5,005	176,758	6.1	24.9	3.6
16 Oct.	4,346	153,478	9.9	21.8	3.7
24 Oct.	4,480	158,220	5.6	25.4	4.2

Table 2. Peak concentration and duration of salinity at Harrington Point (RM 23.4) during eight 24-h surveys. September-October 1977-1978.

Survey	Flow		Maximum tidal range (feet)	Peak concentration (o/oo)	Duration (h)
	(m^3/s)	(cfs)			
1	3,114	109,983	6.8	15.0	18
2	3,270	115,484	9.5	0.0	--
3	3,665	129,454	5.8	16.0	22
4	3,420	120,774	10.1	0.0	--
5	5,149	182,194	9.2	0.0	--
6	5,005	176,758	6.1	8.1	10
7	4,346	153,478	9.9	0.0	--
8	4,480	158,220	5.6	8.8	10

third survey. Salinity concentrations near the bottom remained around 15 ppt throughout this survey. A saltwater intrusion of 1.0 ppt occurred at Grays Point on all high-high and low-low tides during each of the eight surveys.

Maximum concentration of salinity at the Cathlamet Bay site was 19.7 ppt on the third survey. A salt water intrusion occurred at this site during all but the fifth survey.

Salinity data collected at Harrington Point (RM 24.5) shows a saltwater intrusion for all surveys taken during the neap tide cycles; surveys 1, 3, 6, and 8 (Table 2). Salt water did not reach Harrington Point during the four surveys taken on spring tide cycles (Surveys 2, 4, 5, and 7). The highest salinity concentration measured at this site was 16.6 ppt.

Based on previous records, the concentration, extent, and duration of saltwater intrusion into the middle and upper Columbia River estuary (RM 18.2 to 26.5) was greater than expected. Haertel and Osterberg (1967) state maximum salinity in the Columbia River occurs with high tide and low river flow and probably intrudes less than 20 nautical miles (RM 23). Their salinity measurements in the upper estuary were taken at low tide and therefore represent minimum salinity. Lutz et al. (1975) measured salinity throughout the estuary during a September 1969 spring tide cycle (range 7.2 feet). Their records show salinities of less than 10 ppt at Tongue Point (RM 18.2) and less than 2 ppt near RM 20. These concentrations correspond to our salinity data collected during the September 1977 and 1978 spring tide cycles. In October 1972, Misitano (1974) recorded salinities to 22 ppt at Tongue Point (RM 18.2) and salinities to 6.6 ppt at Harrington Point (RM 23.4). These data were collected during a neap tide cycle (tidal range 6.5 feet) at a monthly mean river flow of 4,460 m^3/s (157,500 cfs).

Studies by Haertel (1965) and Neal (1965) indicate that salinities were higher on the northern side of the river (North Channel) than in the main ship channel. This may be true for the lower estuary downstream from the Astoria Bridge (RM 13.6); however, a comparison between salinity data taken on the north side of the river at Grays Point (RM 19.3) and data taken in the main channel at Tongue Point (Rm 18.2) shows much higher salinity concentrations at Tongue Point during seven of our eight surveys. The exception was Survey 7 (16 and 17 October 1978) conducted during the highest tide of the month. Data from this survey shows slightly higher salinities at Grays Point (Grays Point, 9.2 ppt, Tongue Point, 8.5 ppt).

Misitano's (1974) data and our data taken on the monthly neap tide cycles show higher concentrations of salinity, extending farther upstream, and remaining over a longer duration than previous studies. The earlier salinity studies in the upper estuary documented salinities at low tide or during the monthly spring tide cycle. Deepening of the Columbia River bar during the spring and summer of 1977 and the creation of a 40-foot by 600-foot channel through the estuary could also have contributed to the increased intrusion of salt water into the estuary.

RECOMMENDATIONS

If salinity patterns in the Columbia River estuary are changing, then major ecological changes may occur. These changes could affect the distribution of benthic and pelagic fish and shellfish. Invertebrates that are beneficial to the food chain or that could be detrimental to the environment (wood borers or fouling organisms) could be changing in abundance and distribution within the estuary in such a way as to affect major fisheries or impose major impacts at the fishing ports of Ilwaco and Chinook, Washington and Astoria, Oregon. Therefore, salinity intrusion into the Columbia River estuary should be more thoroughly examined and documented in greater temporal and spatial detail.

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CHAPTER 9

FRESHWATER INFLOWS AND THE SAN FRANCISCO BAY COMPLEX

THE NUTRITIONAL SIGNIFICANCE OF THE DISTRIBUTION OF SUSPENDED PARTICULATE MATERIAL IN THE UPPER SAN FRANCISCO BAY-ESTUARY

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ABSTRACT

A study was conducted to investigate the relationship between the distribution of nutritionally important suspended particulate matter and the area of the entrapment zone in upper San Francisco Bay estuary. The biochemical characteristics of the particulate material were measured monthly for a year at salinities of 0, 2, 4, 6 and 10 ppt. The particulate matter was size fractioned into two categories: 0.5 to 15-μ and 0.5 to 120-μ. Samples were analyzed for cholorophyll a, ATP, protein, carbohydrate, and particulate organic and inorganic carbon concentrations. At all salinities evaluated, an average of 78 percent of the protein and 76 percent of the carbohydrate was found in the 0.5 to 15-μ size fraction. From July through December the highest concentrations of suspended particulate matter were reported for the intermediate salinities of 4 and 6 ppt, indicating the presence of an entrapment zone at these salinities. The highest concentrations, of the biochemical components analyzed, occurred in the entrapment zone, except for carbohydrate and detrital carbon. The nutritional quality of the particulate matter, as measured by the protein/carbohydrate ratio, was higher in the entrapment zone than in adjacent upstream or downstream locations. The distribution of filter-feeding zooplankton over the same salinity range indicated rotifers and calanoid copepods were not significantly different between the salinities evaluated. Eurytemora hirundoides was the dominant adult copepod in the entrapment zone. The results indicate the entrapment zone is a nutritionally enhanced area for filter feeders in the estuary. Not all species studied appeared to be able to utilize this resource due to physiological requirements which restrict them to salinities higher or lower than the entrapment zone location.

INTRODUCTION

The northern reach of the San Francisco Bay estuary is characterized by a net two-layered flow circulation pattern during most of the year (Conomos 1979; Conomos and Peterson 1977). The effects of this two-layered flow in conjunction with the physical-chemical processes of flocculation aggregation and settling result in the formation of an area of maximum concentration of suspended materials. This area has been termed the "turbidity maximum" (Conomos and Peterson 1974) or "entrapment zone" (Arthur 1975).

The location of the entrapment zone is determined primarily by the amount of net freshwater inflow to the estuary (Conomos and Peterson 1974; Peterson et al. 1975). During peak outflows (January-March) the entrapment zone may be as far downstream as the Carquinez Strait or San Pablo Bay and during very low inflows (e.g., 1976 drought) the entrapment zone may move as far upstream as Decker Island on the Sacramento River (Figure 1). Arthur and Ball (1980) have presented data which suggest that entrapment zone location has a strong influence on phytoplankton populations. They report that the highest levels of chlorophyll a occur when the entrapment zone is located in the Honker Bay area. They suggest that the presence of the entrapment zone in this shallow, well-mixed bay allows for increased phytoplankton residence time in the photic zone in contrast to when it is in the deep, less well-mixed, narrow channels. They report that the entrapment zone is generally located in Honker Bay when freshwater outflows range from 5,000-8,000 ft^3/sec.

Analysis of historical water quality data has demonstrated that concentrations of chlorophyll, phytoplankton, particulate organic nitrogen and suspended inorganic material are significantly higher in the entrapment zone of the San Francisco Bay estuary than in adjacent upstream or downstream areas (Arthur and Ball 1978). Research in other estuaries has demonstrated that the estuarine circulation cell created by two-layered flow, is an important mechanism for the transport and concentration of zooplankton (Rogers 1940; Cronin et al. 1962; Cronin and Mansueti 1971). Cronin et al. (1962) have pointed out that in two-layered systems, the normal diel vertical migration of zooplankton in response to light would successfully move them between inflowing and outflowing waters over a 24-hour period. This would assist the zooplankton in maintaining a restricted horizontal distribution in the estuary. High concentrations of zooplankton are known to occur in the area of the entrapment zone in the San Francisco Bay estuary (Painter 1966; Turner 1966). Recent studies (Siegfried et al. 1979; Orsi and Knutsen 1979) indicate that high concentrations of the mysid shrimp, Neomysis mercedis, also occur there. The results from these studies, however, have not been able to indicate whether the zooplankton are being concentrated in the entrapment zone by hydrologic forces or whether conditions there, such as food concentration or salinity, are beneficial for the organisms.

As a part of a project investigating the interaction of dissolved organic matter and suspended particulate material in the estuary, we have investigated the distribution of some nutritionally important biochemical characteristics of the suspended particulate material in relation to the entrapment zone. The objectives of this part of the study were to: (1) determine if the entrapment zone is an area where nutritionally important particulate material is accumulated along with the increase in suspended inorganic matter; (2) determine if the nutritional "quality" of this particulate material is different from that in adjacent upstream and downstream areas; and (3) relate the distribution of these nutritionally significant materials to the distribution of filter feeding zooplankton.

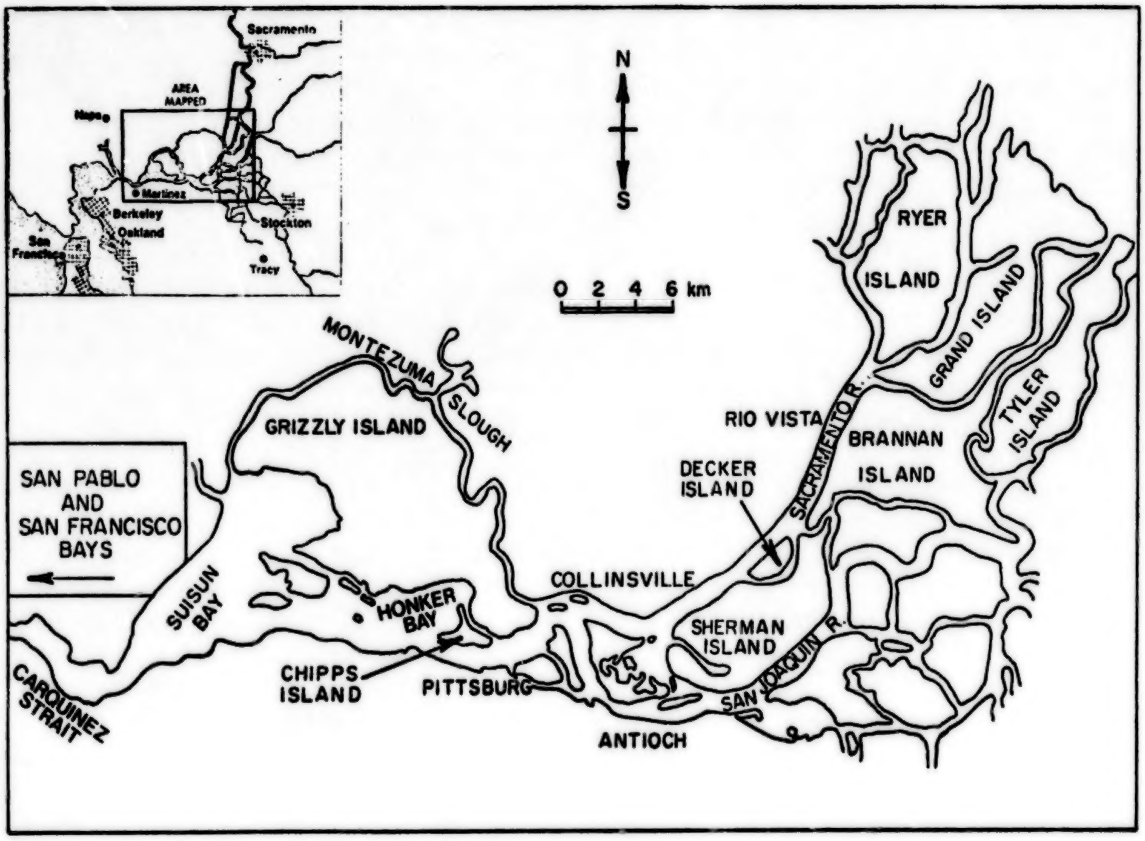

Figure 1. The upper San Francisco Bay estuary.

MATERIALS AND METHODS

The zooplankton and suspended particulate matter samples were collected once a month during 1979 at salinities of 0, 2, 4, 6 and 10 ppt. Salinity was measured with a YSI Model 33 salinity/conductivity meter. All samples were obtained at high tide, one meter off the bottom.

The water samples for particulate matter analysis were collected at each site using a Van Dorn sampler. The sample was filtered through a 120-µ nitex screen to remove all zooplankton. One half of the sample was further filtered through a 10-µ nitrex screen (effective pore size = 15 µ) using the reverse flow process (Dodson and Thomas 1964; Holm-Hansen et al. 1970). The procedure divided the water sample into two particulate matter size fractions for analysis: 0.5 to 120 µ and 0.5 to 15 µ). Samples for analysis of all the biochemical fractions were collected on Reeve Angel 984-H glass fiber filters (effective pore size = 0.5 µ) except for chlorophyll a, which were collected on Whatman GFC filters (effective pore size = 1.0 µ). Samples for chlorophyll a and ATP were filtered immediately after collection in the field. Chlorophyll a and phaeopigments were measured by fluorometry according to the method of Yentsch and Menzel (1963) as modified by Holm-Hansen et al. (1965). ATP was measured as described by Holm-Hansen and Booth (1966) using the enhanced enzyme preparation of Jones and Simon (1977). Particulate living carbon was obtained by multiplying the ATP content by 286 (Holm-Hansen 1970).

The remaining water samples were placed on ice and analyzed for particulate protein, carbohydrate, organic carbon and inorganic carbon content, upon return to the laboratory. Particulate protein was determined by the method of Lowry et al. (1951) as modified by Bensadoun and Weinstein (1976). For particulate carbohydrate content, the phenol-sulfuric acid method (Strickland and Parsons 1968) was employed.

Particulate organic matter concentration was determined by loss of weight on ignition at 475°C to 500°C. Temperatures were maintained below 500°C to avoid errors due to loss of carbonate (Hirota and Szyper 1975). Particulate organic carbon content was calculated by dividing the particulate organic matter concentration by a factor of two. Detrital carbon concentration was calculated by subtracting the living carbon fraction from the particulate organic carbon content.

Triplicate zooplankton samples were collected one meter off the bottom at each site with a portable electric diaphragm pump equipped with a diffuser. The water was pumped into a collecting bottle equipped with a 60-µ screen. The zooplankton were rinsed into jars and preserved in 5 percent buffered formalin plus rose bengal stain.

RESULTS AND DISCUSSION

DISTRIBUTION OF SUSPENDED PARTICULATE MATTER

The area of maximum turbidity in the upper San Francisco Bay estuary generally occurs in water of about 1 to 7 ppt salinity (Ball 1977). We selected sampling sites of 10, 6, 4, 2 and 0 ppt salinity in order to insure sampling upstream and downstream of the entrapment zone. The locations of the sampling sites are shown in Figure 2, along with the mean delta outflow for each sampling time. The data collected for total suspended particulate matter (0.5 to 120µ) indicated the presence of an entrapment zone over the six consecutive months, from July through December 1979. The data for this entire period were pooled by salinity. A one-way ANOVA indicated a significant difference in suspended particulate matter concentration between salinities (Table 1). Scheffe S test (multiple comparison of means) demonstrated that the highest concentration of suspended particulate matter occurred at salinities of 4 and 6 ppt. They were significally different ($P \geq .05$) than the concentration at the other salinities evaluated. Four and 6 ppt salinity was therefore defined as the location of the entrapment zone and we used this definition to test hypotheses relating to food concentration and zooplankton abundance in the entrapment zone.

The data for the nutritionally important biochemical components of the suspended particulate matter were pooled in the manner previously described and analyzed by one-way ANOVA. The results are presented in Table 2. The concentrations (mg/liter) of all the nutritional parameters except carbohydrates and detrital carbon were significantly different between the salinities evaluated. Highest concentration for all of the significant parameters occurred in the entrapment zone. Average particulate protein and carbohydrate concentration in the entrapment zone was 2 to 3 times higher than those at 0 or 10 ppt salinity. This correlates with a twofold to eightfold increase in chlorophyll a concentration within the entrapment zone. Concentrations of all the biochemical components evaluated were always lowest at 0 ppt salinity.

In order to determine if the hydraulic forces in the entrapment zone were selectively concentrating any of the nutritional components more effectively than the inorganic (non-utilizable) fraction, the data were transformed to a mg nutritional component/mg suspended particulate matter basis. Results indicated that there was no significant difference ($P \geq .05$) in concentration between salinity for any of the parameters evaluated. This indicates that the nutritionally important suspended materials are accumulating in the entrapment zone at the same rate as the inorganic fraction (e.g., suspended silts and clay) is accumulating. The inorganic fraction reported for the entrapment zone ranged from 79 to 89 percent of the total suspended particulate by weight.

During the sampling period (July to December 1979) and at all salinities, the majority of the proteins and carbohydrates (mg liter) was found in the 0.5 to 15-µ size fraction of the particulate material. An average of 78 percent (range = 58% to 96%) of the protein and 76 percent (range = 50% to 94%) of the carbohydrates was found in the 0.5 to 15µ size fraction. Mayzaud and Taguchi (1979) reported similar results when studying the distribution of biochemical components in the suspended matter of the Bedford Basin, Canada. They noted that most of the protein reported was contained in the 18-µ size fraction. The higher concentration of protein and carbohydrates in the 0.5 to 15-µ size fraction of the San Francisco Bay estuary particulates does not mean that the smaller particulates are richer in these components on a mg nutritional component per mg suspended particulate matter basis. The average amount of suspended particulate matter in the 0.5 to 15-µ size fraction is 78 percent of the total particulate matter. This is the same value as for the nutritional component indicating the large and small particles may have about the same average biochemical composition.

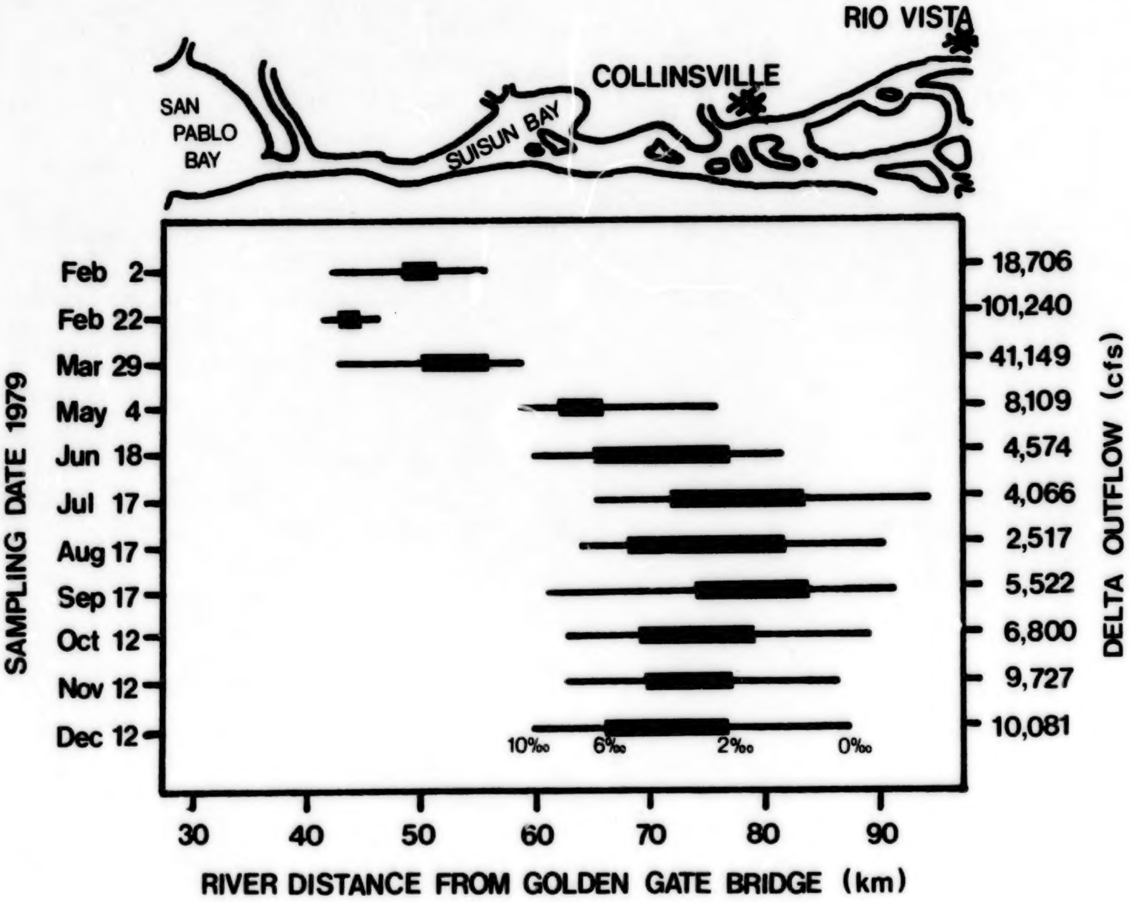

Figure 2. Location of the 0 to 10 ppt salinity gradient for the sampling dates in 1979. The dark portion of the bars indicates the estimated location of the entrapment zone based on the 2 to 6 ppt salinity range.

Table 1. Analysis of variance test of the hypothesis that the suspended particulate matter concentration does not differ between the salinities evaluated.

	MEAN CONCENTRATIONS FOR JULY-DECEMBER 1979, POOLED BY SALINITY					F-STATISTIC[1]	SCHEFFE S MULTIPLE CONTRAST[1]
	0‰	2‰	4‰	6‰	10‰	(4,25 df)	4,6‰ versus 0,2,10‰
SUSPENDED PARTICULATES (mg/ℓ)	39.44	67.76	105.57	98.32	60.28	4.92**	*

[1] * $P \leq .05$, ** $P \leq .01$

Table 2. Analysis of variance tests of the hypothesis that the concentrations of the suspended particulate components do not differ between the salinities evaluated.

SUSPENDED PARTICULATE COMPONENT	MEAN CONCENTRATIONS FOR JULY-DECEMBER 1979, POOLED BY SALINITY					F-STATISTIC[1]	SCHEFFE S MULTIPLE CONTRAST[1]
	0‰	2‰	4‰	6‰	10‰	(4,25 df)	4,6‰ versus 0,2,10‰
CHLOROPHYLL a (μg/ℓ)	2.80	11.33	23.51	26.16	12.07	3.50*	*
ATP (mg/ℓ)	2.73	7.03	13.14	11.85	6.45	4.55**	*
PROTEIN (mg/ℓ)	0.73	1.54	2.57	2.57	1.26	6.38***	*
CARBOHYDRATE (mg/ℓ)	1.26	1.98	2.73	2.76	2.03	1.99 N.S.	—
PROTEIN/CARBOHYDRATE RATIO	0.65	0.82	0.98	0.94	0.67	3.70*	*
PARTICULATE INORGANIC CARBON (mg/ℓ)	27.96	58.94	91.41	84.40	51.98	5.75**	*
PARTICULATE ORGANIC CARBON (mg/ℓ)	2.42	4.41	7.07	6.96	4.16	6.73***	*
DETRITAL CARBON (mg/ℓ)	1.66	2.58	3.47	3.57	2.49	1.13 N.S.	—

[1] * $P \leq .05$, ** $P \leq .01$, *** $P \leq .001$, N.S. not significant.

NUTRITIONAL QUALITY OF THE PARTICULATE MATTER

Boyd and Goodyear (1971) indicate that for general ecological purposes, quantifying the amount of protein and amount of noncell wall carbohydrates in organic matter is a good measure of the nutritional quality of net production. Nutritional quality is defined as that portion of the organic matter of the food that is nutritionally utilizable by a consumer. They report that the level of protein seems to be the most important factor. A protein/carbohydrate ratio, therefore, would serve as a good index of the nutritional quality of suspended particulate matter in aquatic systems. Our data (Table 2) indicate that the highest average protein/carbohydrate ratios occur within the entrapment zone. The entrapment zone, therefore appears to be an area in the estuary that is nutritionally enhanced for filter feeding organisms, both in terms of food concentration and food quality.

DISTRIBUTION OF FILTER FEEDING ZOOPLANKTON

The distribution of three dominant types of filter feeding zooplankton in the upper San Francisco Bay estuary was analyzed. The organisms were rotifers, calanoid copepod nauplii, and adult calanoid copepods. Transformed zooplankton abundance enumerations were used in the statistical analysis. The transformation log (x+1) was chosen so as to bring the distribution of abundance values closer to a normal distribution and to reduce the dependence of the variance on the mean.

The data for abundances of adult calanoid copepods indicate no significant difference between abundances and the salinities evaluated (Table 3). This indicates that factors other than hydraulic forces or food concentration may be affecting their distribution. The dominant species of calanoid copepods during the study were Acartia clausi, Eurytemora hirundoides, and Limnocalanus macrurus. Both Acartia and Eurytemora have been reported to be selective filter feeders, selecting for particle biomass peaks, and for larger particles (Allan et al. 1977; Donaghay and Small 1979). Based on these feeding strategies, we would expect to find both of these species in the entrapment zone where maximum food abundance occurs. The relative abundance of the three dominant species at each of the salinities evaluated is shown in Table 4. E. hirundoides is the dominant copepod in the entrapment zone. The maximum abundances of both A. clausi and L. macrurrus occur at the salinities outside the entrapment zone. A. clausi is the most abundant calanoid copepod at 10 ppt and L. macrurus was the most abundant at 0 and 2 ppt salinity. A clausi is considered to be a more haline species than E. hirundoides (Kelly 1966) and is found throughout the San Francisco Bay estuary at higher salinities (Aplin 1967; Caskey 1976). The zooplankton abundance data reported by Arthur and Ball (1978) indicate that A. clausi is the dominant copepod species in the upper estuary at salinities greater than 8 ppt. A. clausi, therefore, appears to be limited in its distribution to more saline waters probably due to physiological requirements.

L. macrurus also appears to be limited by physiological requirements to the lower salinities evaluated in this study. L. macrurus is a relict species, meaning a saltwater form tember 1977 and 1978 spring tide cycles. In October 1972, Misitano (1974) recorded salinities to 22 ppt at Tongue Point (RM 18.2) and salini-

If salinity patterns in the Columbia River estuary are changing,

Ecology 43:459-472, 1967.

Lutz, G.A.; Hubbeel, D.W.; Stevens, H.H., Jr. Discharge and flow

lected data during at least one of the 24-h surveys. Special thanks to Nancy Know and Alta Scott for tabulation and typing.

Table 3. **Analysis of variance test of the hypothesis that the abundance of various filter feeding zooplankton do not differ between the salinities evaluated. [ANOVA performed on abundance transformed by log (x+1)].**

FILTER FEEDING ZOOPLANKTON	MEAN ABUNDANCE FOR JULY-DECEMBER 1979, POOLED BY SALINITY					F-STATISTIC[1]	SCHEFFE S MULTIPLE CONTRAST[1]
	0‰	2‰	4‰	6‰	10‰	(4,25 df)	4,6,10‰ versus 0,2‰
ROTIFERS (number/m^3)	522	3728	11345	9503	6402	3.67*	*
COPEPOD NAUPLII (number/m^3)	3081	13246	27765	34866	28674	3.83**	*
CALANOID COPEPODS (number/m^3)	2205	1829	2872	2114	3986	0.478 N.S.	—

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[1] * $P \le .05$, ** $P \le .01$, N.S. not significant

Table 4. Mean abundances for the calanoid copepod species, pooled by salinity for July-December 1979

CALANOID COPEPOD SPECIES	SALINITY				
	10‰	6‰	4‰	2‰	0‰
ACARTIA CLAUSI (number/m^3)	2870	465	29	55	0
EURYTEMORA HIRUNDOIDES (number/m^3)	638	1416	2154	713	463
LIMNOCALANUS MACRURUS (number/m^3)	478	233	689	1061	1742

that has become acclimated to freshwater. It is generally found in the deep waters of large lakes in the United States and Europe (Pennak 1978).

Of the three dominant species of adult calanoid copepods investigated during this study, only E. hirundoides appears to be able to capitalize on the maximum food abundances occurring in the entrapment zone. E. hirundoides is an euryhaline species. Caskey (1976) found E. hirundoides at salinities from 0 to 25 ppt, with most occurring at 2 to 12 ppt salinity. Arthur and Ball (1978) reported E. hirundoides to be predominant in the area of maximum suspended solids concentration. Siegfried et al. (1976) reported that Eurytemora undergoes a diel vertical migration in the San Francisco Bay estuary. This behavioral adaptation could be important in maintaining Eurytemora in the entrapment zone as described earlier.

The data indicated a significant relationship between rotifer, and calanoid copepod nauplii abundance, and salinity (Table 3) A Scheffe S multiple contrast of the means indicated that the abundances at 4, 6, and 10 ppt salinity were higher and significantly different than those at 0 and 2 ppt salinity. The occurrence of maximum abundances at 10 ppt salinity as well as in the entrapment zone could be the result of the dominant species of each of these filter feeders migrating into the entrapment zone from higher salinities. The rotifer Synchaeta sp. was the most abundant rotifer during the study. Synchaeta sp. has been reported to occur throughout the entire estuary (Caskey 1976) usually in more saline waters (Siegfried et al. 1978). Sitts and Knight (1979) found Synchaeta sp. abundance tended to increase with salinity over diel cycles indicating migration from higher salinities.

The high number of copepod nauplii at 10 ppt could be due to a large concentration of Acartia nauplii at this salinity. They may have salinity tolerances similar to the adults, and are therefore restricted to the more saline water. We were unable to confirm this directly as the nauplii in this study were not identified to species.

CONCLUSIONS

1. The entrapment zone in the San Francisco Bay estuary is an important hydrodynamic feature of the estuary. Its formation and location in the estuary is regulated by the amounts of freshwater inflow to the estuary.
2. The concentration (mg/liter) of nutritionally important compounds within the entrapment zone is 2 to 4 times the concentration of that which occurs upstream and downstream of this estuarine circulation cell. Concentrations of nutritional materials were not significantly different between salinity when compared on a mg component/mg suspended particulate matter indicating that the inorganic components are accumulating at the same rate as the organic matter in the entrapment zone.
3. The nutritional quality of the particulate matter in the entrapment zone is higher than that upstream or downstream of the entrapment zone.
4. Both calanoid copepod nauplii and rotifers occurred at high levels in the entrapment zone.

The distribution of adult calanoid copepods is not positively correlated with the area of the entrapment zone. When analyzed by species however, Eurytemora hirundoides is the dominant adult copepod in the entrapment zone. The two other dominant species of adult copepods appear to be restricted from the high food concentrations of the entrapment zone by physiological requirements for a higher or lower salinity.

5. Since the entrapment zone appears to be an area of high food abundance and high food quality, research should continue into the factors controlling the formation and location of this estuarine circulation cell. The entrapment zone appears to be an important link in the physical, chemical, and biological processes regulating productivity of the estuary. Continued study of the entrapment zone may help to understand the mechanisms through which variations in freshwater inflow can lead to changes in the productivity of the estuary.

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DISCUSSION

Question: Rick Sitts, Ecological Analysts, Concord California: Did you notice any difference in the carbohydrate and protein contents of sediments when the entrapment zone was off the shallows of Suisun Bay versus when it might have been upstream in the narrow channels? And second, do you think that food availability is limiting the production?

Answer: We haven't analyzed the data yet by location. We are doing a study in one of the marshes right now in the narrow channels. In the narrow channels in the marsh areas there is a much higher protein/carbohydrate ratio, than out in the major channels. I don't have any of that data organized to present yet. We haven't analyzed it in terms of zooplankton abundance and feeding rates, so I couldn't say if they are food limited right now or not.

Question: Joseph Mihursky: University of Maryland. Have there been any larval food habit studies to look at the larval fish utilization of the different zooplankton species?

Answer: The people at the Fish and Wildlife Service would know that. The only other studies I've known in relation to zooplankton or other types of organisms in the entrapment zone was Jim Orci's work with California Fish and Game, and he found a predominance of Neomysis in the entrapment zone, especially on the freshwater end. But I don't know of any larval fish feedings studies that have been done yet.

Question: Are there any planned or on the way?

Answer: Maybe Rick can support what I'll say. I know some larval fish work has been done before I got to California.

Question: What I'm asking about is larval fish collections made at the same time zooplankton collections are made to go along with the additional data you have on zooplankton in terms of stomach content and selection of food?

Answer: I don't believe that the specific work has been done on selected feeding. But California Fish and Game has had a tow net survey for larval stripped bass and eggs for a number of recent years but to my knowledge I don't believe they did the actual selective feeding-type analysis. I think that it would be very useful to do so. As Marty said, California Fish and Game has collected a large number of samples (about 4,000 stomach contents from 1968-73), but available data is for 1971-73, and it covers size ranges of striped bass from 5 to about 25 millimeters.

EFFECTS OF FRESHWATER FLOW ON FISHERY RESOURCES IN THE SACRAMENTO-SAN JOAQUIN ESTUARY

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ABSTRACT

Over twenty years of biological and hydrological studies in the Sacramento-San Joaquin Estuary have documented changes in magnitude and timing of freshwater flow associated with water development in the watershed. These changes, coupled with natural fluctuations in flow, stimulate ecological relationships that largely control the survival and distributions of various fish and invertebrates. Specifically, the magnitude of delta outflow and water diversions are major factors controlling survival of striped bass (*Morone saxatilis*) during their first two months of life. Likewise, annual abundance indices for young fall run chinook salmon (*Oncorhynchus tshawytscha*), American shad (*Alosa sapidissima*), and longfin smelt (*Spirinchus thaleichthys*) also increase directly with river flow rates during the spawning and nursery periods. High flows increase disperal of young fish which may decrease density dependent mortality. Overall abundance of opossum shrimp (*Neomysis mercedis*), the principal food of several fish and invertebrates, appears to be reduced by salinity-incursion (lower flows) and increased water diversions. Salinity intrusion resulting from low flows also stimulates dispersal of salt-water species into more of the estuary, while habitat for freshwater species is reduced. Although previous study emphasis and documentation of effects of water development have occurred principally in the upper estuary, freshwater flow may affect biological communities in San Pablo and San Francisco bays too. A two-year study focusing on juvenile dungeness crab (*Cancer magister*) in these bays concluded that high spring runoff caused crabs to move into more saline waters and probably out of the bay. Present studies are designed to examine the relationship between reduced flows and bay area fishery resources in more detail. Such studies are necessary since freshwater flow to the ocean has been approximately halved since the 1800's and will be reduced even further in the future.

INTRODUCTION

Over twenty years of biological and hydrological studies in the Sacramento-San Joaquin Estuary have documented changes in magnitude and timing of freshwater flow which are associated with water development in the watershed. These changes, coupled with natural fluctuations in flow, control the survival and distribution of various fishes and invertebrates. It is important to understand the implications of these changes and concomitant ecological relationships so intelligent management decisions can be made when the inevitable conflict between water-development projects and fish and wildlife resources occurs. It is the intent of this paper to summarize the current knowledge of the effects of estuarine hydrology on fishery resources in the Sacramento-San Joaquin Estuary. Much of the information discussed was obtained from studies completed as part of a four-agency (California Department of Fish and Game, California Department of Water Resources, U.S. Fish and Wildlife Service, and U.S. Water and Power Resources Service) agreement. The water development agencies finance roughly two-thirds of the biological research and also conduct their own studies on hydrological and water quality impacts on project operations. Part of this work was funded by Dingell-Johnson Project, California F-9-R, "A Study of Sturgeon, Striped Bass, and Resident Fishes", supported by Federal Aid to Fish Restoration funds.

DESCRIPTION OF ESTUARY

The confluence of the Sacramento and San Joaquin river systems forms a complex estuary characterized by interconnected embayments, sloughs, marshes, channels, and rivers (Figure 1).

The delta forms the easternmost portion of the estuary. It is bounded by the Sacramento River on the north and by the San Joaquin River on the south. Approximately 1,130 km (702 miles) of channels interlace this triangularly shaped area and surround large cultivated islands that were reclaimed from naturally occurring marshes in the late nineteenth and early twentieth centuries. These channels vary in width from about 50 m (164 ft) to 1.5 km (0.93 miles) and are generally less than 15 m (50 ft) deep.

Suisun, San Pablo, and San Francisco bays are to the west of the delta. They cover an area of about 1,125 km^2 (434 mi^2). The bays are relatively shallow, with a mean depth of 6 m (20 ft) at mean low water, although they are incised by narrow channels (natural and dredged) that are typically 10 to 20 m (32 to 65 ft) deep. The deepest sections of channel (e.g. Golden Gate, 110 m [360 ft] and Carquinez Strait, 27 m [88 ft]) are topographic constrictions whose depths appear to be maintained by tidal currents (Conomos 1979).

The estuary has a Mediterranean climate. The San Francisco Bay area is dominated by the ocean and therefore is characterized by warm winters, cool summers, and minimal seasonal temperature variation. Average July air temperature is 15°C (59°F) while average January temperature is 10°C (50°F). The ocean's influence is modified with increasing distance inland. The delta area has a continental climate with a mean July air temperature at Stockton of 23°C (73°F) and a mean January temperature of 7°C (45°F). Kelley (1966) describes the estuary in detail.

The estuary receives runoff from a 163,000 km^2 (63,000 mi^2) drainage basin which covers 40 percent of the land area of California (Conomos 1979). Inflow into the system is highly seasonal and is composed primarily of rain runoff during winter and snowmelt runoff during early summer (Figure 2). The annual natural flow through the estuary would average about 34 km^3 (27.6 X 10^6 acre-ft), but consumptive uses and diversions in and stream from the delta have halved this amount. Ninety percent of the fresh water that enters the bay passes through the delta (Porterfield et al. 1961) and Carquinez Strait. Delta outflow is not measured directly but relative values

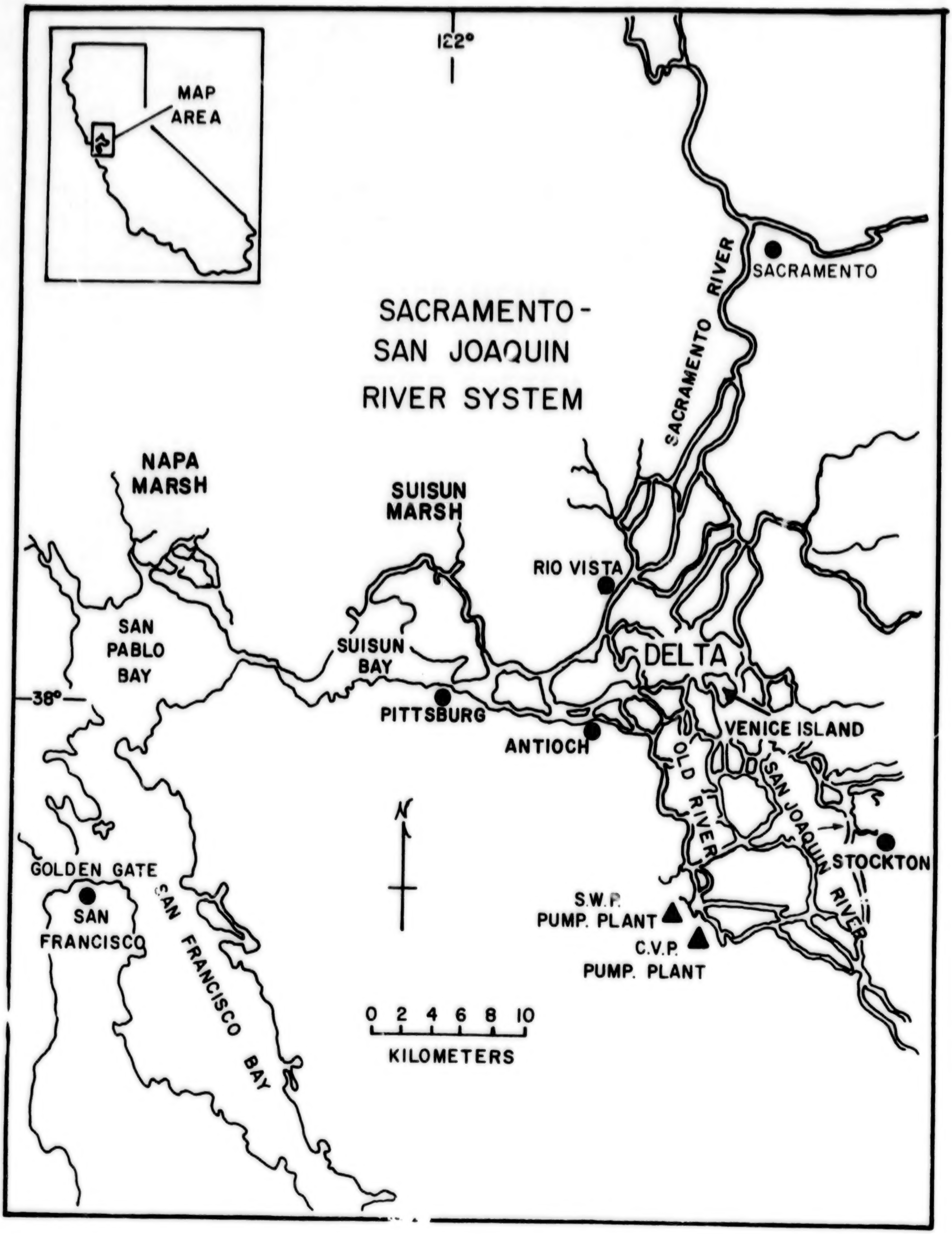

Figure 1. Sacramento-San Joaquin River System.

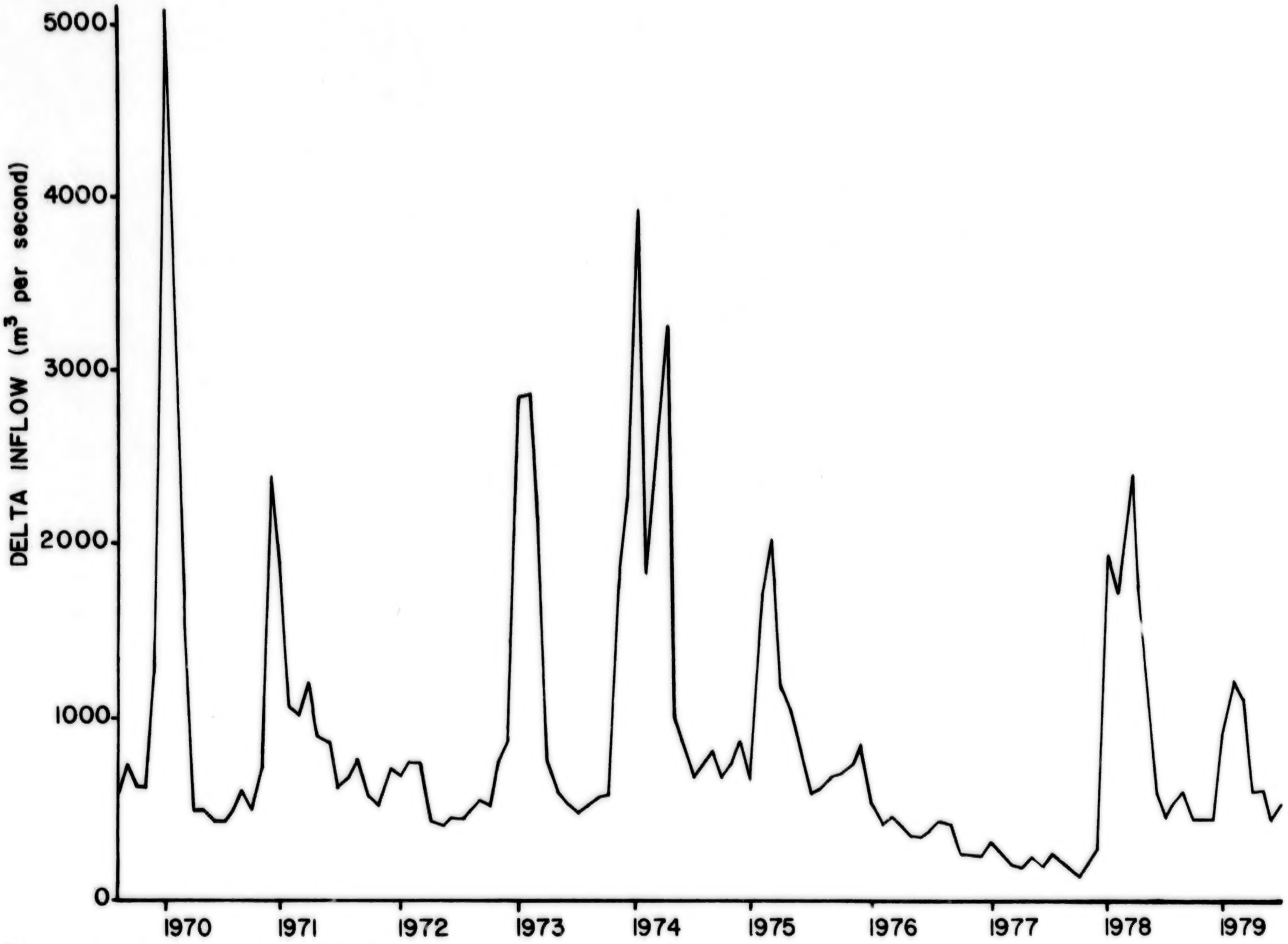

Figure 2. Inflow into system by month.

Seasonal changes in salinity distributions within the system result from tidal exchange and river inflow. River inflow varies widely so it has a greater system-wide seasonal effect (Conomos 1979). San Francisco Bay is usually nearly as saline as the ocean. The gradient from sea to fresh water generally begins in San Pablo Bay and extends about 80 km (50 mi) to the western delta. This longitudinal salinity gradient ranges from 30 ppt at the Golden Gate to less than 1 ppt at the Delta. The general region of the gradient where the landward flow of seawater compensates the seaward flow of fresh water has been termed the "null zone" (Conomos and Peterson 1974, Peterson et al. 1975). In about the same general region occupied by the null zone certain suspended materials (including the biota) accumulate in what has been termed the "entrapment zone" (Arthur and Ball 1978). The location of this area is largely dependent upon the amount of freshwater flow, but is usually in Suisun Bay during the spring through fall period.

Nontidal currents in the estuary are generated by winds and river flow. Velocities of such currents are one-tenth those of tidal currents, yet they are important in transporting dissolved and particulate substances into and from the bay (Conomos 1979). These landward-flowing bottom currents are driven by gravitational circulation and are affected by the magnitude of delta outflow. These currents are strongest and most consistent in the central and northern reaches of the bay because of the influence of the delta outflows and greater stratification which occurs there (Peterson et al. 1975). Gravitational circulation is much weaker in South Bay since there are few freshwater inputs in that part of the system. Other high outflow related processes such as "increased dilution discharge" and increased baroclinic circulation enhance circulation there (Fischer and Kirkland 1978).

Increased demand for domestic and agricultural water in the more arid southern part of the State has resulted in the construction of large State and Federal water development projects. These projects have altered the hydrology of the estuary through dam and reservior construction, estuarine and upstream diversions, and transport facility construction and operation. The San Joaquin drainage has been almost completely developed for upstream use. Development of the Sacramento system has been designed to transport water through the delta for use in the south. Inflows from the two river systems into the delta are not equal. From 1970 to 1975 an average of 88 percent of the inflow to the delta came from the Sacremento River.

Water is exported to the south by two large pumping plants in the southwestern delta (Figure 1). These plants, built by the U.S. Water and Power Resources Service and the California Department of Water Resources have a combined pumping capacity of 300 m^3/s (10,500 cfs). Typical export rates substantially exceed the flow of the San Joaquin River; therefore most water comes from the Sacramento River. Sacramento River water must pass through channels too small to carry the required diversion flows, so export rates greater than 100 m^3/s (3,500 cfs) draw water up the San Joaquin River and delta channels from their junctions with the Sacramento River. Such net upstream flows in the San Joaquin River are typical in the spring, except in wet years, and in the summer and fall of all years.

EFFECTS OF DIVERSIONS AND FRESH-WATER FLOW ON FISHERIES

Changes in distributions and survival of various fish and invertebrates in the Sacramento-San Joaquin Estuary have occurred in response to direct and indirect effects of diversions and project-altered amounts of freshwater flow.

Direct Effects of Diversions

The most obvious biological impact of the water projects is the transport of young fish and pelagic fish eggs to the diversion sites. Attempts are made to "salvage" the large numbers of fish which arrive at the pump facilities each year. Annual "salvage" estimates for 1968-1979 have ranged up to 42 million striped bass (Morone saxatilis), 4 million American shad (Alosa sapidissima), 500,000 chinook salmon (Oncorhynchus tshawytscha), and 18 million individuals of 43 other species (Stevens and Chadwick 1979). Unfortunately, due to behavioral peculiarities or poor swimming ability, many more fish are not salvaged because they pass through the project louver screens. Skinner (1974) estimated that 31 percent of the striped bass, 25 percent of the chinook salmon, and 78 percent of the white catfish (Ictalurus catus) were lost through the screens. The estimate for striped bass is a minimum because Skinner's estimates did not include larvae, for which louvers are entirely ineffective. Additional losses of "salvaged" fish which occur during holding, trucking, and release have not been thoroughly evaluated, but they probably are substantial. Preliminary information suggests that handling and trucking causes mortality on the order of 20 to 60 percent.

From 1959 to 1976 variations in survival of young striped bass were directly correlated with variations in river flow and inversely correlated with rates at which water was diverted from the delta by local agriculture and Federal and State water projects (Chadwick et al. 1977). Abundance of young bass was reduced as outflows decreased and as diversion rates increased apparently because the diversions removed a greater fraction of the flow and fish when flows were not high enough to transport the young fish to Suisun Bay. We concluded (Chadwick et al. 1977) that diversions acted as a density-independent source of mortality, actually cropping a portion of the population during the first few months of life. However, in 1977, 1978, and 1979 young bass abundance indices averaged 32 percent lower than expected from the prior relationships between abundance, flow, and diversion rates. Hence, some additional factor(s) has caused recent abundance to fall below levels accounted for by the analysis for previous years and at present we can not explain why.

Indirect Effects of Diversions

Several examples of indirecteffects of diversions which adversely impact the Sacramento-San Joaquin fishery resources have been documented. (1) Flow reversals, associated with pumping in the south delta, cause young and adult anadromous fish to migrate across the delta toward the pumps, rather than through the delta to the ocean. Such deviation from direct migration routes to the ocean apparently leads to increased mortality of young salmon (Kjelson et al. 1981) and probably other species. (2) A few post-spawning adult striped bass, American shad, and white sturgeon (Acipenser transmontanus) follow these flows to the trashracks at the salvage facilities (Stevens and Chadwick 1979). Here these fish fight the current until they die of exhaustion. (3) Starting in 1961, salmon runs of the San Joaquin, but not of the Sacramento, suffered a disastrous collapse due in part to delayed migration resulting from poor water conditions and flow reversal in the San Joaquin part of the delta. Salmon orientation apparently was affected by the large flow of Sacramento River water which was diverted through various delta channels and sloughs (Hallock et al. 1970). (4) Export pumping increases flow velocities in channels that carry Sacramento River water across the delta to the pumping plants. This results in reduced standing crops of important fish food organisms, benthos, and zooplankton such as copepods, cladocerans, and Neomysis mercedis (Hazel and Kelley 1966; Turner 1966; Heubach 1969). High flow velocities depress populations of benthic organisms because sandy channel bottoms become unstable, and plankton populations do not get a chance to grow when "residence times" are short.

Amount of Freshwater Flow

The amount of freshwater flow passing seaward through the delta affects the distribution of fish and fish food organisms in the estuary. For example; (1) The proportion of young striped bass in downstream nursery areas increases as flow increases (Turner and Chadwick 1972). (2) The opossum shrimp (Neomysis mercedis) is hydraulically and behaviorally concentrated just upstream of the "entrapment zone." Since the zone's location moves in relation to flow, changes in shrimp distributions also occur (Orsi and Knutson 1979). (3) River flow controls the distribution of young salmon, shad, and longfin smelt (Spirinchus thaleichthys) in the system because high flows disperse them to downstream areas (Stevens and Miller, Calif. Dept. Fish and Game MS; Kjelson et al. 1981). (4) Ongoing studies in central and south San Francisco Bay indicate that freshwater flow-related bay circulation affects the distribution of English sole (Parophrys vetulus). Stronger and more consistent bottom flows in the northern area generally cause more ocean-spawned young sole to be swept into North Bay than to the South Bay where gravitational circulation is less. However, from 1980 data (Figure 3), we hypothesize that high flows (high enough to initiate baroclinic circulation) may disperse sole in the bay by carrying greater numbers of young into the South Bay. (5) In response to large delta outflows and subsequent reduced salinities throughout the bay, dungeness crabs (Cancer magister) consolidate in areas of salinity greater than 10 ppt before emigrating out of the bay (Tasto, Calif. Dept. Fish and Game MS). This flow-regulated consolidation occurs in April-May and by the end of summer movement out of the bay and mortality account for the loss of greater than 90 percent of the outgoing class. (6) The species composition of fish in the Suisun and Napa Marsh sloughs varies with salinity and flow (Figure 4). During a 1975 to 1978 survey of 10 sloughs in these marshes, we collected 40 freshwater, estuarine (euryhaline or anadromous), and marine species (Table 1). Salinity increased substantially in both marshes in 1977 due to a prolonged

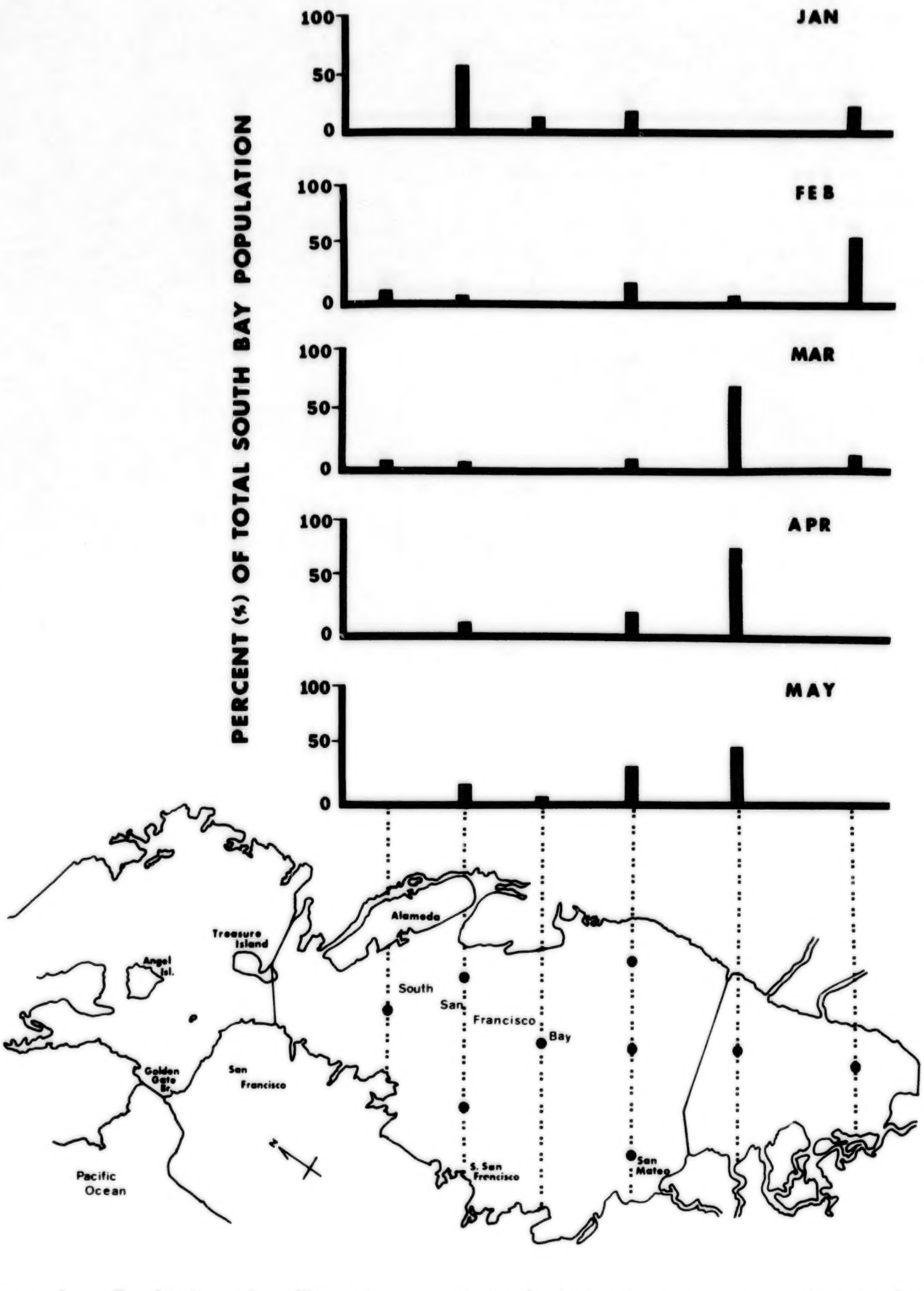

Figure 3. English sole (Parophrys vetulus) distribution in south San Francisco Bay during January - May, 1980 based on catch-per-unit-effort. Mean conductivities (micromoles) for the period were: January - 27145, February - 19870, April - 33856, May - 30602.

drought. In the Suisan Marsh the salinity increase caused abundance of freshwater fish to decrease markedly and abundance of marine species to increase slightly. In the Napa Marsh, except during high freshwater flows in winter, salinities always were intolerable to most freshwater species so their abundance always was low. The low abundance of estuarine species in the Napa Marsh in 1976 and 1977 was striking. Possibly this reflected low "dispersion flows" rather than salinity tolerances. As expected, marine species increased in the Napa Marsh in 1976 as salinity was increasing during the first year of the drought. However, abundance of marine fishes decreased in 1977 even though salinity was higher then. Apparently other factors limited the invasion of the marsh by marine species that year.

The amount of freshwater flow also affects the abundance of fish and their food organisms. As explained previously, from 1959 to 1976 young-of-the-year striped bass abundance indices were directly correlated with flow (Turner and Chadwick 1972; Chadwick et al. 1977). Also, increased survival associated with increased flow was a major factor affecting abundance of recruits 3 years later (Figure 5) (Stevens 1977).

Abundance indices for young fall run chinook salmon, American shad, and longfin smelt are highly correlated with river flow rates during spawning and nursery months (Stevens and Miller, Calif. Dept. Fish and Game MS). Likewise, a multiple regression analysis for data collected during 1969 through 1978, indicates that 88 percent of the variation in N. mercedis abundance is due to salinity near Pittsburg (a reflection of the magnitude of delta outflow) and mean chlorophyll a concentration (Knutson and Orsi Calif. Dept. Fish and Game MS).

The relationships between distribution and survival of the various species and amounts of freshwater flow are potentially caused by several mechanisms, the importance of which may vary among the species. These mechanisms include: (1) Flow-regulated transportation towards or away from diversions: Increased flows carry young fish seaward thus decreasing their vulnerability to diversion. (2) Increased habitat availability: Increased flows disperse young fish into areas not otherwise available, probably resulting in decreased inter- and intraspecific competition and less predation than when the young fish are concentrated in a smaller part of the river system. (3) Increased food availability: In the estuary, nutrient supplies which form the basis of the food chain may increase with flow, causing increased productivity (Turner and Chadwick 1972). Also, productivity of the entrapment zone (Ball 1977, Arthur and Ball 1978) and abundance of a major food organism (Neomysis mercedis), for fish are affected by the location of the salinity gradient which is determined by flow (Knutson and Orsi, Calif. Dept. Fish and Game MS). (4) Suitability of spawning habitat: Extremely low flows such as in 1977 reduce striped bass spawning habitat because salinity intrudes into the delta and water in the San Joaquin River upstream from the delta is of poor quality due to a high proportion of the flow being formed by agriculture waste water. Secondly, in the river above the delta, salmon mortality probably increases when reduced flows cause redds to become exposed (Stevens and Miller, Calif. Dept. Fish and Game MS).

Table 1. Classification of fishes collected in the Suisun and Napa Marshes in 1975-78 into freshwater, estuarine, and marine groups.

Freshwater	Estuarine	Marine
Carp *Cyprinus carpio*	Striped bass *Morone saxatilis*	Pacific herring *Clupea harengus pallasi*
Sacramento squawfish *Ptychocheilus grandis*	Splittail *Pogonichthys macrolepidotus*	Speckled sanddab *Citharichthys stigmaeus*
Sacramento blackfish *Orthodon microlepidotus*	Threadfin shad *Dorosoma petenense*	California halibut *Paralichthys californicus*
Hitch *Lavinia exilicauda*	American shad *Alosa sapidissima*	Shiner perch *Cymatogaster aggregata*
Goldfish *Carassius auratus*	Starry flounder *Platichthys stellatus*	Pile perch *Rhacochilus vacca*
Sacramento sucker *Catostomus occidentalis*	Tule perch *Hysterocarpus traski*	Surf smelt *Hypomesus pretiosus*
White catfish *Ictalurus catus*	Yellowfin goby *Acanthogobius flavimanus*	Northern anchovy *Engraulis mordax*
Brown Bullhead *Ictalurus nebulosis*	Delta smelt *Hypomesus transpacificus*	White croaker *Genyonemus lineatus*
Black bullhead *Ictalurus melas*	Longfin smelt *Spirinchus thaleichthys*	Bay pipefish *Syngnathus griseolineatus*
Channel catfish *Ictalurus punctatus*	Threespine stickleback *Gasterosteus aculeatus*	Pacific tomcod *Microgadus proximus*
Prickly sculpin *Cottus asper*	Steelhead rainbow trout *Salmo gairdneri*	Plainfin midshipman *Porichthys notatus*

Table 1. Continued

Freshwater	Estuarine	Marine
Black crappie *Pomoxis nigromaculatus*	White sturgeon *Acipenser transmontanus*	Pacific staghorn sculpin *Leptocottus armatus*
Bluegill *Lepomis macrochirus*		
Sacramento perch *Ambloplites rupestris*		
Largemouth bass *Micropterus salmoides*		
Mosquitofish *Gambusia affinis*		

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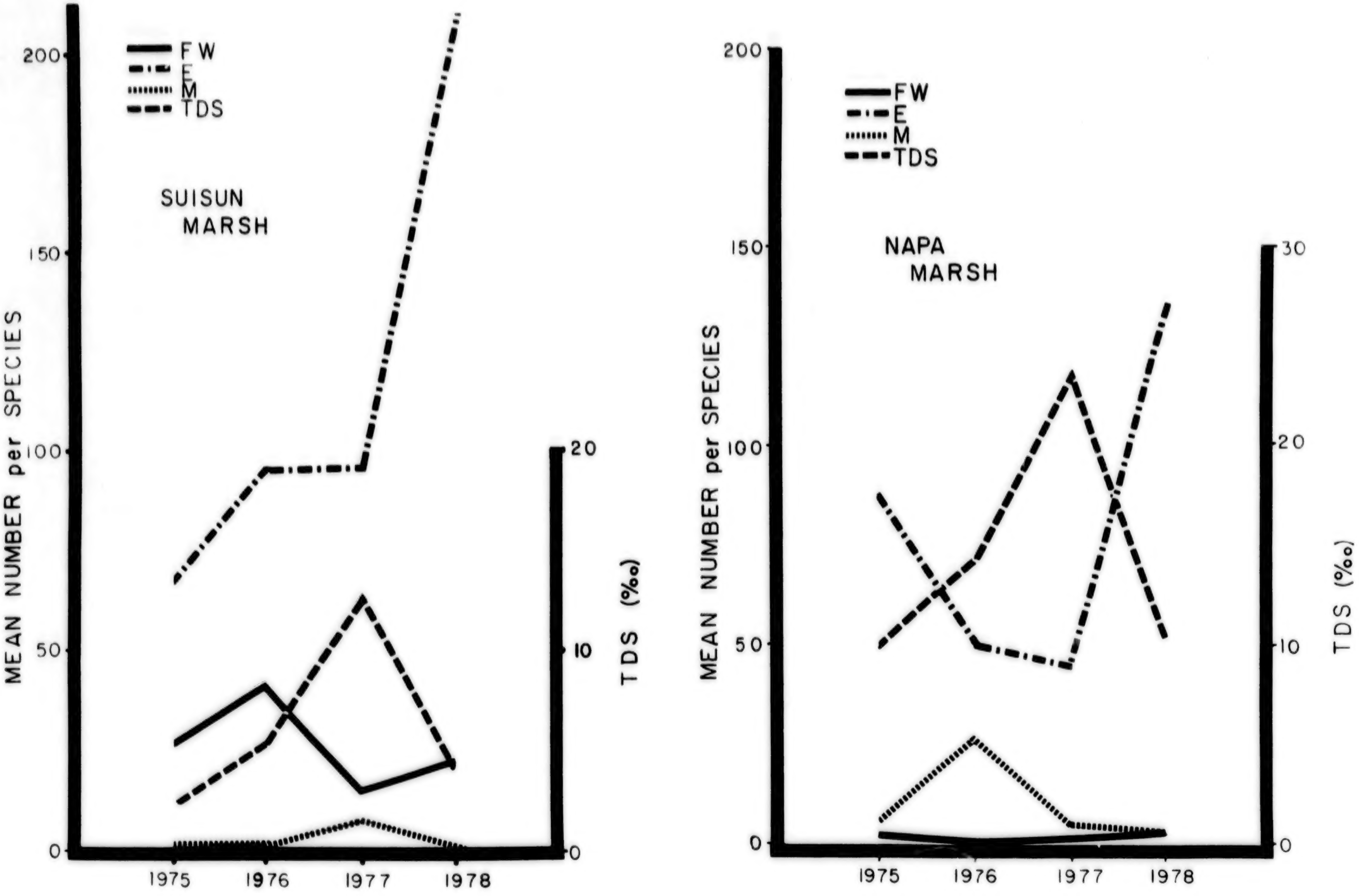

Figure 4. Changes in abundance of fishes, grouped by salinity tolerance, in Suisun and Napa marshes, 1975-78. Salinity or total dissolved solids (ppt.) shown for comparison. FW - freshwater species; E - estuarine species; M - marine species.

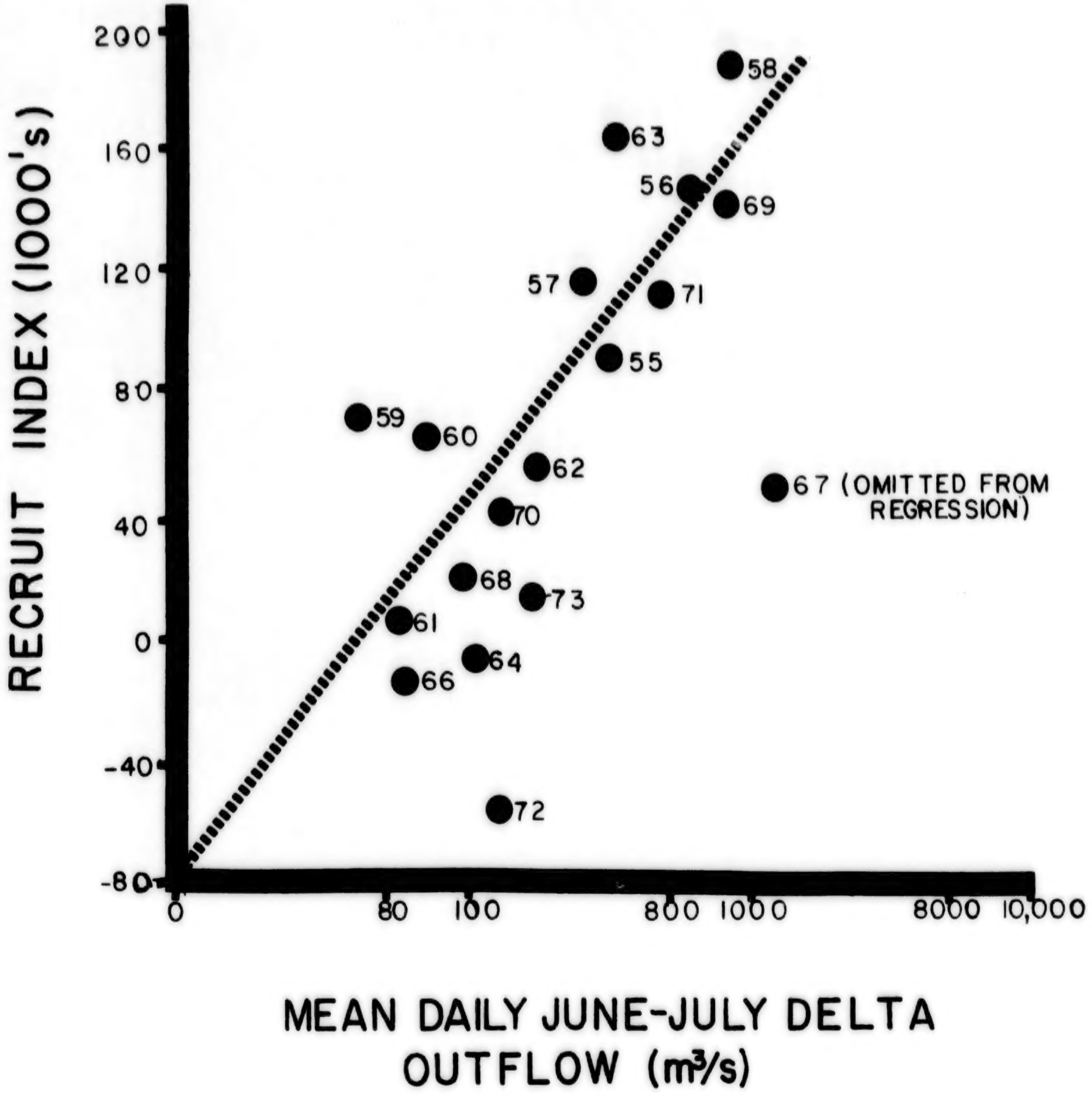

Figure 5. Relationship between index of abundance of three year old striped bass and mean daily freshwater outflow from the Sacramento-San Joaquin Delta during June and July, three years earlier. Numbers adjacent to points indicate year classes over the period 1956-73.

FUTURE ACTIVITIES

Since the turn of the century, freshwater flows into the estuary have been substantially reduced in fall, winter, and spring while summer flows have increased slightly. Overall flow reductions are projected to continue (Figure 6) and will impact the estuarine ecosystem. To date documentation of the importance of freshwater flow in this system has been concentrated in the fresh and brackish water areas; however, studies to evaluate potential adverse effects in the saltier San Francisco and San Pablo bays is justified by many unanswered questions about the biological-hydrological dynamics of the total system. Hence, our department, in conjunction with the other three Ecological Program agencies has initiated a long-term study to determine the importance of freshwater flow for San Francisco and San Pablo Bay fish and wildlife resources.

The Delta Outflow/San Francisco Bay Study will concentrate on how outflow-related changes in hydraulics and salinity will affect fish and wildlife distributions and survival in San Francisco and San Pablo bays. The objectives will be met initially by carrying out seven field and analytically oriented study elements. The program will investigate the effects of reduced flow on circulation patterns, salinity gradients, nutrients, organic detritus, suspended sediments, and silt loads. Simple field techniques (e.g. drouges, etc.) will be used to investigate current patterns and attempts will be made to improve the technical understanding of existing simulation models (both physical and numerical) and the estuary. We anticipate that the improved understanding of the hydraulics of the bay and delta and the importance of that to the biological systems will allow us to project the effect of various hydraulic schemes on bay fish and wildlife.

The biological components of our program include a monthly field sampling effort to obtain information on fish and invertebrate population dynamics and distributions at 35 locations in the system. Adult fish are sampled with otter and midwater trawls; larval fish, fish eggs, and some invertebrates are collected with an egg and larval net; and beach seine samples are taken at 28 sites along the shoreline. Information collected includes species composition, size distributions, and food habits. A major component of the investigation will be the development of abundance indices for Crangon and Pala-mon shrimp. These shrimp indices will be used as an indicator of the health of the system, as it is perturbated by flow alterations.

The Delta Outflow/San Francisco Bay Study is scheduled to continue for at least six years. During this time the program undoubtedly will evolve in response to early findings.

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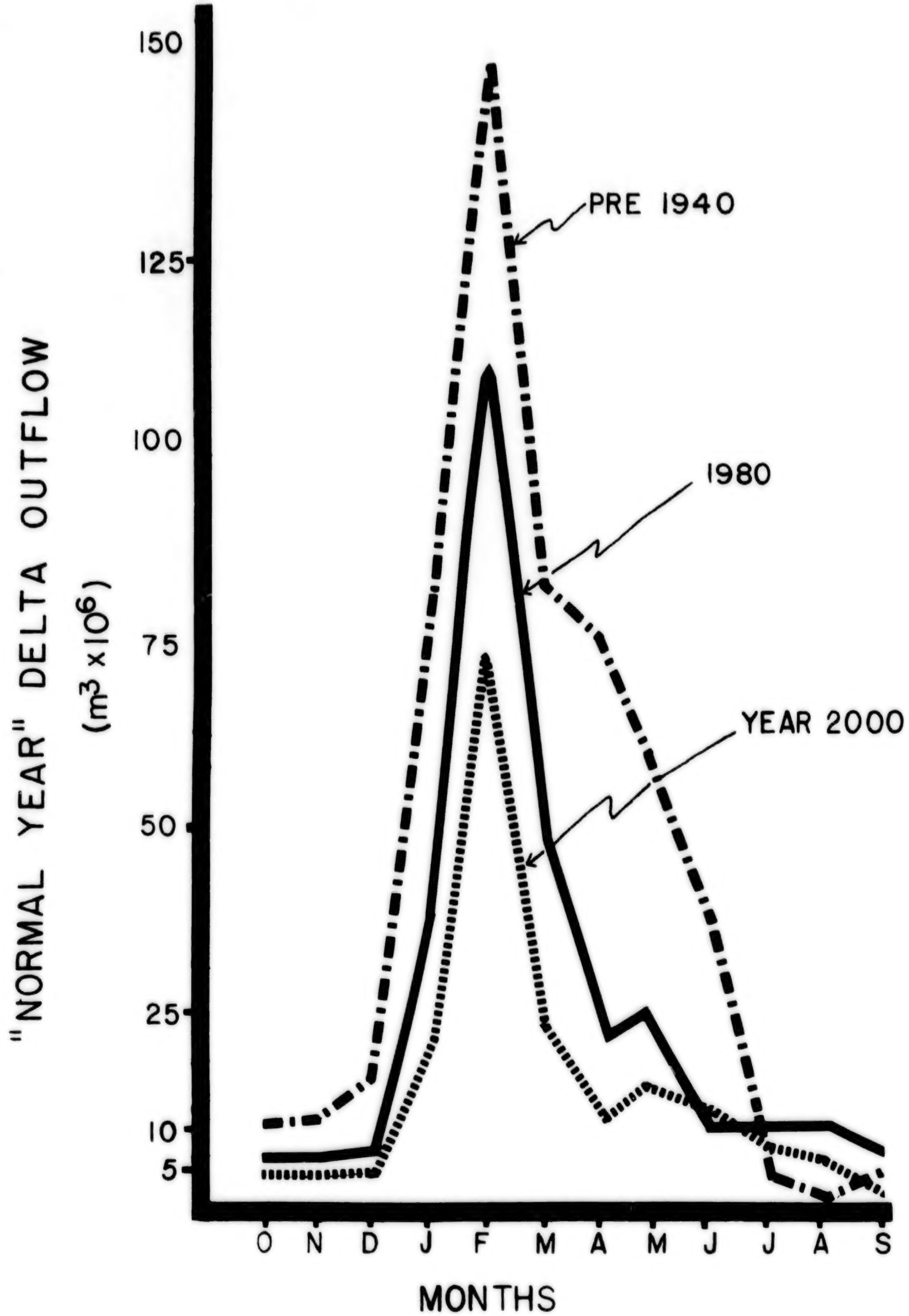

Figure 6. Trends in freshwater outflow from Sacramento-San Joaquin Delta. Values are for "normal year". (Based on October - September 1936). Figure adapted from Association of Bay Area Governments Environmental Management Plan, June 1978.

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DISCUSSION

Question: Norm Benson, Fish and Wildlife Service: Perry, when you say habitat availability has increased, you mean by the size of the entrapment zone?

Answer: When large amounts of freshwater moves into the system, it moves into the system, the location of the entrapment zone moves further towards Suisun Bay and San Pablo Bay. If you remember the map, those areas are flatter and broader; therefore, the actual area of the zone is increased. During low flow years, like 76-77, the entrapment zone was up in the narrow river channel where the area is not nearly as great. Another factor is some of the salmon work that Stevens and Miller have been working on. This work shows that those increased flows also improve the areas where fish are spawning. So outflow improves that habitat as well as increases the area available for fish.

INFLUENCES OF FRESHWATER INFLOW ON CHINOOK SALMON

(ONCORHYNCHUS TSHAWYTSCHA)

IN THE SACRAMENTO-SAN JOAQUIN ESTUARY

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ABSTRACT

This paper describes present knowledge regarding the influence of freshwater inflow on the survival, abundance, migration and rearing of chinook salmon in the upstream (delta) portion of the Sacramento-San Joaquin Estuary. Preliminary results indicate that additional inflow at the appropriate time will increase the numbers of fry and juvenile salmon using the estuary and the survival of juveniles in the estuary. Results are based on seine and trawl surveys, salmon collections at water diversion fish screens, and mark-recapture techniques. Flow-related concerns for salmon in the estuary stem from (1) water development activities that have altered the distribution of flow resulting in impacts on young and adult migration, and (2) the lack of comprehensive flow standards with which to protect salmon. Future efforts to better quantify salmon flow needs include long-term seine and trawl surveys in both the upper and lower portions of the estuary, as well as intensive, replicated marking experiments done under varied flow conditions and supported by estuarine, ocean and inland recovery programs.

INTRODUCTION

Freshwater inflow is a dominant factor that influences the character of estuaries and in turn their ability to provide for the life history needs of anadromous salmonids that use these systems for migration and rearing.

Chinook salmon and steelhead trout (Salmo gairdneri) are the principal salmonids utilizing the Sacramento-San Joaquin Estuary. On a price-per-pound basis, chinook are the most valuable of the Pacific salmon, and only the Columbia River system produces more than California's Central Valley rivers (California Department of Fish and Game 1976). These California rivers supply about 75 percent of the state's ocean commercial catch of over 500,000 chinook and probably contribute a similar fraction to both the ocean and inland sport fishery harvest of more than

125,000 fish annually (Ganssle 1962, California Department of Fish and Game 1976).

Specific information documenting the importance of freshwater inflow to chinook salmon while inhabiting the estuary has been limited. Recent studies, designed to define the impacts of water development on the estuary's fish and wildlife resources, have provided new information regarding the importance of freshwater flows to salmon. More information, however, is needed to develop a sound management program that best meets salmon life history needs. These studies have concentrated on the upper (Sacramento-San Joaquin Delta) portion of the estuary (Figure 1). Only recently, 1980, has data specific to salmon been collected from the lower (San Francisco-San Pablo bays) portion of the system.

The purpose of this paper is (1) to summarize our present knowledge of the influences of freshwater inflow to chinook salmon in the Sacramento-San Joaquin Estuary, (2) to describe the methods utilized to obtain this knowledge, and (3) to summarize our present estuarine research activities with chinook salmon.

Most of the information discussed within this paper is based upon studies completed and planned as part of the cooperative (Four Agency) Ecological Study Program for the Sacramento-San Joaquin Estuary between the California Department of Fish and Game (CFG), California Department of Water Resources, United States Fish and Wildlife Service and the United States Water and Power Resources Service. While our paper is specific to chinook salmon/flow relationships, a more general review of fishery resources in the Sacramento-San Joaquin System is provided by Herrgesell et al. (1981) in the proceedings of this symposium.

LIFE HISTORY OF CHINOOK SALMON

Chinook salmon are anadromous fish, spawning in fresh water and spending much of their life in saltwater. Eggs are buried in stream gravel associated with rapid current. Depending on water temperature, eggs hatch after approximately 50 to 60 days incubation, and the fry move up through and emerge from the gravel in about 30 days. There is considerable variation as to the time of downstream movement with some fish initiating migration as soon as they emerge while others remain upstream for more than a year.

Residence time in the estuary prior to their movement to sea also is variable with some fish using it for rearing while others pass through quickly. Chinook generally remain in the ocean from one to four years. Following maturation, salmon move upstream through the estuary and spawn, usually in the same drainage system from which they hatched as young. Chinook adults die following spawning (for futher review see Heubach 1968, Jensen 1972, and California Fish and Game 1976).

Over 90 percent of the Central Valley's chinook are produced in the Sacramento River system (California Department of Fish and Game 1976). Four major runs (fall, late fall, winter, and spring) identified by the season in which upmigration and spawning occurs, spawn in the Sacramento system (Hallock and Fry 1967). Figure 2 provides a description of the timing of migration for the fall, winter, and spring runs. While less well understood, the late fall run appears to follow a similar pattern to that of the fall run, but

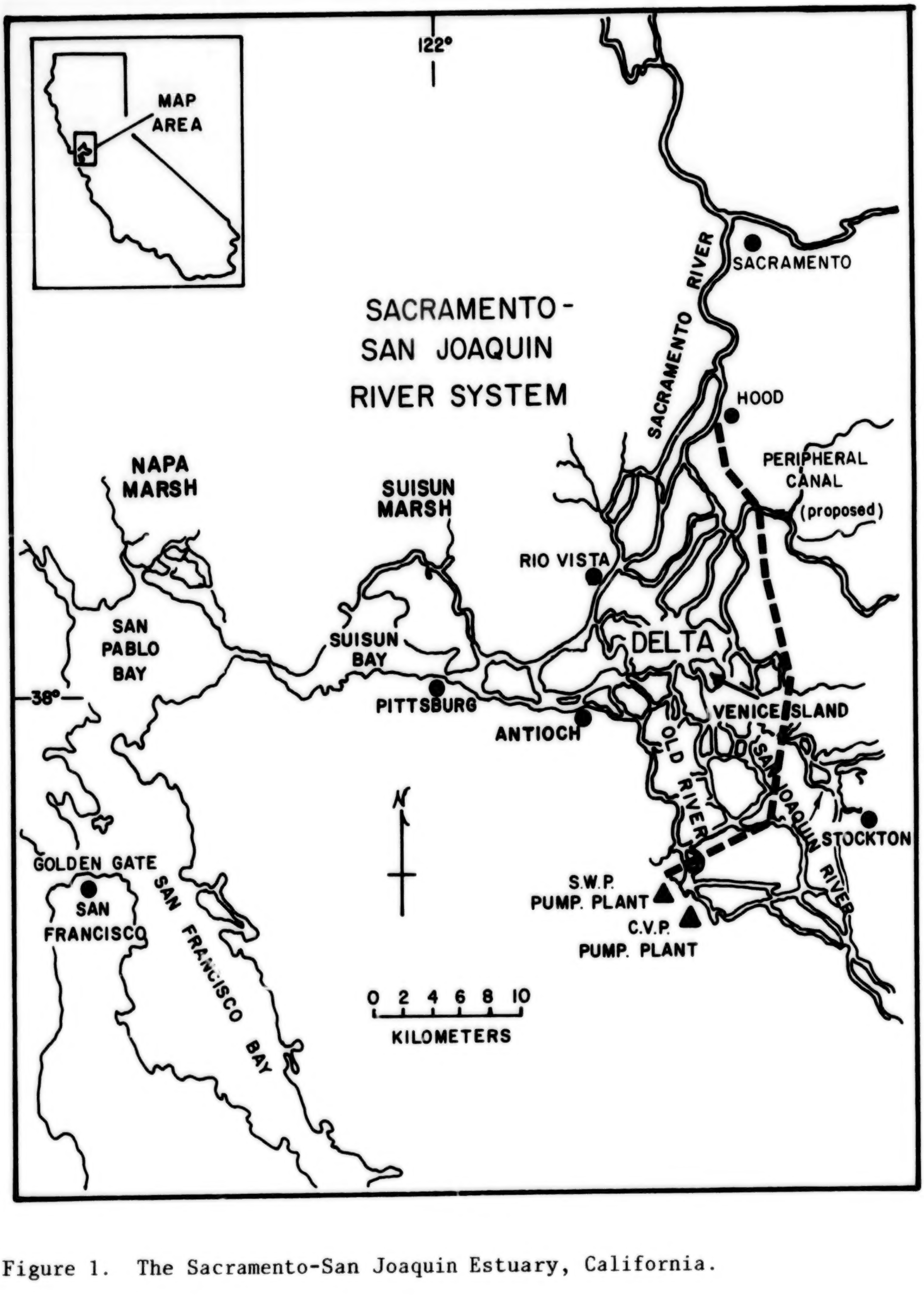

Figure 1. The Sacramento-San Joaquin Estuary, California.

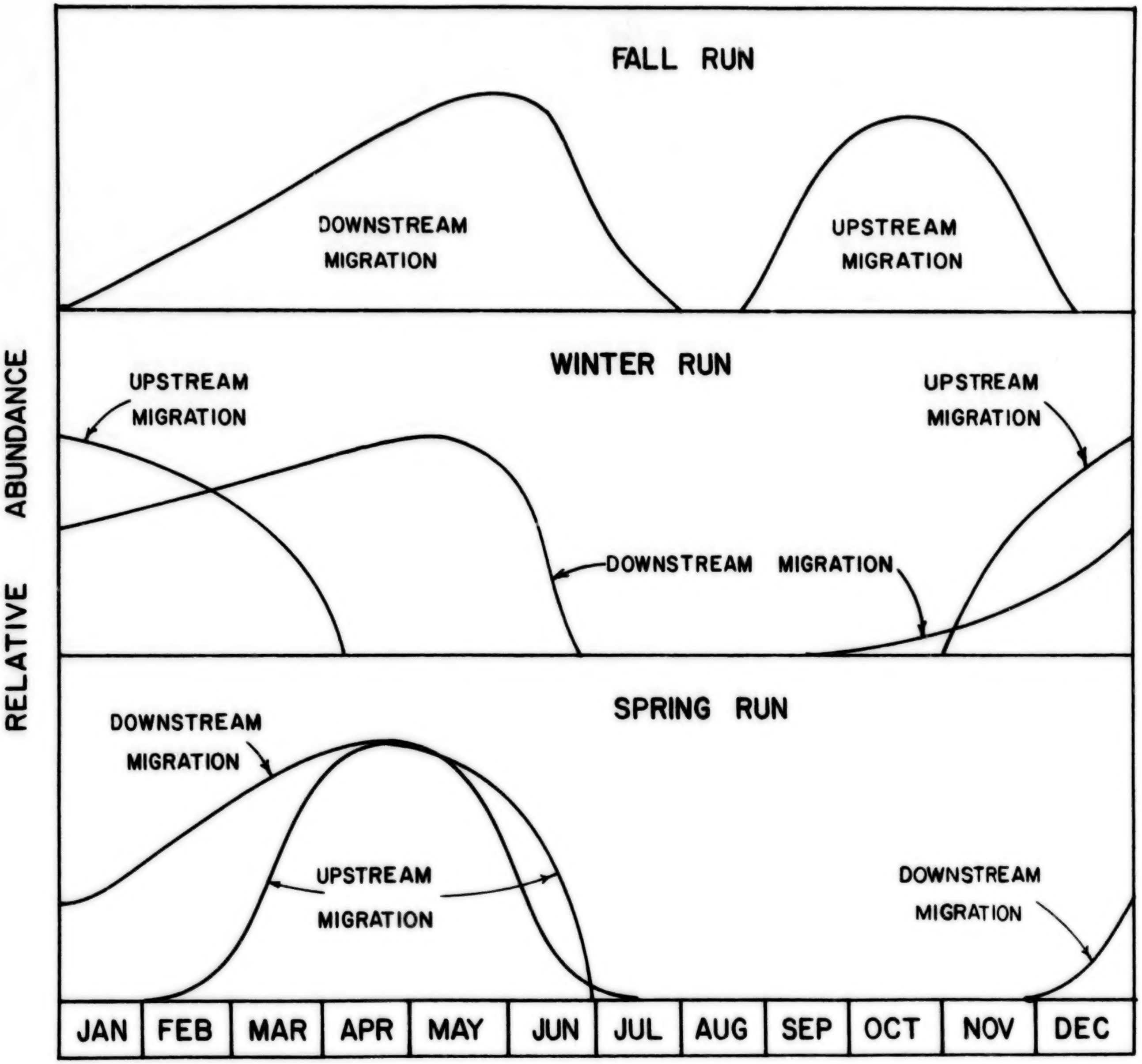

Figure 2. Seasonal migrations and spawning periods of three major runs of Sacramento River chinook salmon in the Sacramento-San Joaquin Estuary.

is approximately a month later. The Sacramento fall run is largest in numbers (140,000 to 300,000 between 1964 and 1977). The San Joaquin River systems supports only a fall run. Numbers since 1973 were less than 10,000 fish (Hoopaugh and Knutson 1979). The assemblage of runs results in salmon inhabiting both the estuary and river habitats in the Central Valley throughout the year.

STUDY AREA

The Sacramento-San Joaquin Estuary is formed by the Sacramento and San Joaquin Rivers joining and flowing through a series of embayments to the Pacific Ocean. These rivers comprise the two major drainage systems of California's Central Valley. The large lowland area formed by the junction of these two rivers is known as the Sacramento-San Joaquin Delta. The delta is triangular in shape and is bounded by Sacramento on the north, Pittsburg on the west and the easternmost point of the San Joaquin River as shown in Figure 1.

The delta is composed of 298,660 hectares (738,000 acres) of land and water. There are 1,130 kilometers (700 miles) of navigable channels and 30 large, leveed below-sea-level islands. Tidal action occurs to the upstream limit of the delta. Some delta channels are edged by narrow stretches of intertidal marsh but most of them have steep banks of mud and riprap. Delta levees are covered by riparian vegetation. Detailed descriptions of both the upper (delta) and lower (bays) portions of the estuary are provided by Kelley (1966), Skinner (1962) and Conomos (1979) as well as by Herrgesell et al. (1981) and other authors in the proceedings of this symposium.

WATER DEVELOPMENT

Water development projects in California have caused major changes in the flow patterns within the estuary and the amount of flow entering the ocean. One result of upstream development is that the average annual freshwater flow to the ocean from the Sacramento-San Joaquin system has been halved since the 1800's. Most of the water in the San Joaquin system is captured and utilized in upstream areas, while development on the Sacramento has been designed for both upstream use and the transport of water through the delta to more southern parts of California. Ninety percent of the freshwater inflow to the estuary is from the Sacramento River.

Presently, water is exported to the south by pumping plants in the southern delta (Figure 1) operated by the Central Valley Project (CVP) of the Federal Water and Power Resources Service and the State Water Project (SWP) of the California Department of Water Resources. Typical export rates substantially exceed the flow of the San Joaquin River, hence most of the San Joaquin flow goes to the pumps. Remaining export needs are met by diversions from the Sacramento River. A part of the flow from the Sacramento crosses the delta through channels upstream from the mouth of the San Joaquin. The dimensions of these channels are too small to carry larger flows, so at higher export rates water is drawn up the San Joaquin from its junction with the Sacramento. Such net upstream flows (reverse flows) in the San Joaquin are typical in the spring, except in wet years, and in the summer and fall of all years (Chadwick et al. 1977).

Future water development plans, as authorized under recent State legislation (Senate Bill 200, signed July, 1980), include construction of additional upstream storage reservoirs and a peripheral canal. The Peripheral Canal Project is designed to divert water at a maximum of approximately 650 m^3/s (23,000 ft^3/s) from the Sacramento River at Hood and transport it around the eastern edge of the delta to the pumps in the southern delta (Figure 1). More detailed discussion of water development in the estuary is provided by the California Department of Water Resources (1978).

Such water development has altered and will continue to alter the character of freshwater inflow to the Sacramento-San Joaquin Estuary. These alterations have the potential to change the survival of chinook salmon and may affect the adult population size. Water development impacts on salmon in more upstream waters have been more obvious, particularly those relating to dam construction where large amounts of spawning and rearing habitat have simply been lost. The operations of delta water development facilities influence estuarine migrations of young and adults as well as estuarine rearing by juveniles.

RESULTS AND FUTURE STUDIES

Our knowledge concerning the influence of freshwater inflow on chinook salmon populations in the Central Valley has been obtained through observations of the annual and seasonal variation in salmon abundance, migration and survival as the magnitude, distribution and quality of river flow has fluctuated. Changes in the character of freshwater inflow is the result of both variation in natural weather patterns and operations of water development projects in upstream and estuarine waters. Annual and spring variation in the quantity of freshwater inflow to the estuary is primarily influenced by annual weather patterns. Summer inflow is influenced most by project reservoir releases. However, a peripheral canal and additional upstream storage reservoirs would temper both the annual and seasonal inflow variation considerably. The distribution of flow in the various channels of the delta is presently altered by the design and operation of the State and Federal water projects. The quality of inflow is influenced by natural weather patterns and water project operations through their impact on flow magnitude which affects dilution of municipal, agricultural and industrial discharges, particularly in the San Joaquin drainage.

The major goals of our salmon studies are: (1) to define the impacts of water development upon estuarine salmon population and (2) to document the water quality requirements (including flow standards) that salmon need to both sustain and enhance their populations. Past experience with striped bass has emphasized that only though long-term efforts can we expect to achieve such goals (Chadwick 1977). Present delta water quality standards, set by the State Water Resources Control Board (Johns 1981) provide some protection for salmon, but are limited by our incomplete knowledge.

VARIATION IN THE QUANTITY OF FLOW

Fry Migration to the Estuary

Spring seine surveys in the delta and the resulting weekly abundance index based on the mean number of fish per haul, indicate that peak catches of salmon fry often follow flow increases associated with storm runoff (Figure 3). This information suggests that flow surges influence the numbers of fry that migrate from upper river spawning grounds into the estuary. Hence, increased flow velocities associated with high runoff apparently increase the rate of migration for fry.

Regression analysis indicated that there was a significant relation between the mean monthly index of fry abundance and mean monthly inflow to the delta. However, flow only accounted for 30 percent of the variation in the abundance index. Data from 1980 appear biased downward since, although it was an extremely high flow year, salmon were observed in San Francisco and San Pablo Bays but these numbers are not reflected in the index. Hence, the number of salmon in the estuary might be more closely related to flow than indicated by the regression. Nevertheless, the total number of fry that potentially migrate to the estuary and rear there prior to their entrance to the sea appears to be influenced by a variety of factors.

Many of these factors appear to be associated with the rivers above the estuary. The number of fry available for estuarine rearing may be influenced by the number of fall spawners (Painter et al. 1977), spawning and incubation flows (Stevens and Miller, CFG unpublished MS), and the numbers of fish already using upper river rearing habitat as new fry emerge (Reimers 1968). The low numbers of fry in the delta during the drought of 1977 and moderate numbers in 1978 (Figure 3) may be primarily due to the poor spawning and incubation flows that existed in the fall of 1976 and 1977, respectively.

Our present and future mark-recapture studies, and seining and trawling surveys emphasize study of the effects of freshwater inflow on fry migrations and comparions between the survival of estuarine- and river-reared fry. The latter will help establish the importance of estuarine rearing to adult stock abundance. Fish are marked with adipose fin clips and implanted with coded wire nose tags (CWT) (Jeffers et al. 1963; Opdycke and Zajac 1980), which have been successfully used with fry as small as 45 mm. Clipping the adipose fin allows for identification later. Releases are being made in the upper river and estuary. Marked juveniles are recovered during our routine seine and trawl surveys in the estuary, and adults by sampling in the ocean fishery and at hatcheries.

Additional studies have been initiated in San Pablo and San Francisco Bays to document the freshwater requirements in the lower estuary. We know that salmon use the bays as a migration route, but the extent of rearing there is unknown. As noted earlier, salmon fry were observed in the central part of San Francisco Bay following large river flows during January and February 1980. Salinities were up to 26 ppt. A release of 50,000 fry, marked with CWTs, was made in the Central Bay during this period. Four of these fish were recovered in the bay several weeks later. Survival estimates of these fish will be made from data on ocean recoveries beginning in 1981. A portion of the future field work in 1981 by the Four Agency's San Francisco Bay Study Program (see Herrgesell et al. 1981, for details) is designed to document the distribution and relative abundance of salmon in the bay via surface trawl and beach seine surveys on a year round basis.

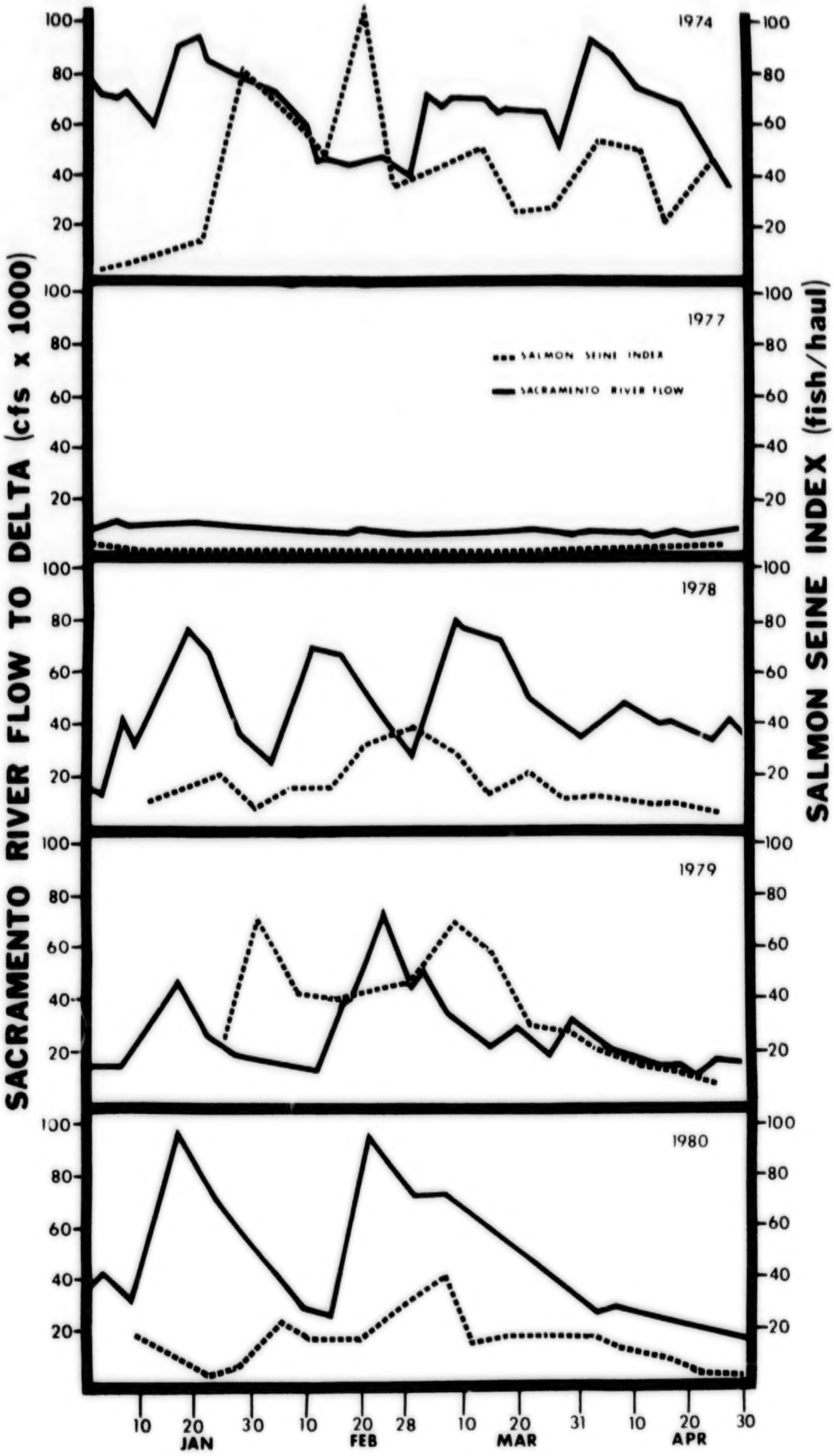

Figure 3. Sacramento River inflow to the Sacramento-San Joaquin Delta at Sacramento and chinook salmon seine indices for the years 1974 and 1977 through 1980. The abundance indices for salmon fry were determined by weekly seine surveys throughout the Delta. 1 cfs = 0.03 m^3.

Juvenile Abundance in the Delta

Flows in the upper Sacramento and San Joaquin rivers during spawning and nursery periods apparently influence the numbers of juvenile chinook surviving to migrate to the delta. This conclusion is based first on correlations between annual abundance indices for chinook and inflow to the delta (Stevens and Miller, CFG unpublished MS). December and January appeared to be the most important months. The abundance indices are based upon catches at the State/Federal fish screens in the south delta from April to June and from an annual delta midwater trawl survey (September to December).

Secondly, observations made in the San Joaquin system between 1957 and 1973 indicate that numbers of chinook spawners are influenced by the amount of river flow during the nursery and downstream migration period (March to June) 2.5 years earlier (Figure 4). Thus, it appears that flow affects juvenile survival which in turn affects adult abundance. Several factors may cause this relation between abundance and flow. Dams and diversions have reduced flows to near minimum levels in most years in the San Joaquin drainage and the high water temperatures that occur concurrently kill many juvenile salmon (California Department of Fish and Game 1976). Hence, the earlier these downstream migrants leave the spawning grounds the better their chance of reaching the estuary. Juveniles entering the estuary early in their development may also require additional growth before migrating to salt water which suggests that conditions in the estuary may be important for at least part of the San Joaquin downstream migrants. One major factor in the delta may be pumping by the State and Federal water projects. Probably a high fraction of the San Joaquin downstream migrants are exposed to the pumping plant screening systems (see later section entitled Juvenile Migration) as most of the San Joaquin flow is diverted during peak outmigration in most years. Poor water quality due to agricultural return flows in the San Joaquin in the fall also may influence the survival of returning adults which may contribute to variation in the numbers of downstream migrants (Figure 4).

Juvenile Survival in the Delta

A regression of estimated juvenile survival rate against river flow suggests that river flow influences chinook survival during downstream migration through the delta (Figure 5). Survival was estimated during 1969, 1970, and 1971 by comparing ocean return rates from fish marked and released as juveniles in the upper and lower delta (California Department of Fish and Game 1976). Estimates for the other years are based on recoveries of juveniles released above the delta and recaptured by trawling at stations in both the upper and lower delta. Some of these fish were marked with spray dye (1976-1977), while others were marked by the CWT technique (1978-1980).

Verification of our initial estimates of survival based on trawling recoveries from 1978 to 1980 will be made by comparing ocean catches of fish from the same releases and another "control" release downstream from the delta in Suisun Bay (Figure 1). Preliminary ocean recoveries obtained from the sport and commercial fisheries in 1979 and 1980 confirmed our initial estimate of survival, close to 0 percent in 1978 (Figure 5). Interestingly the 1979 and 1980

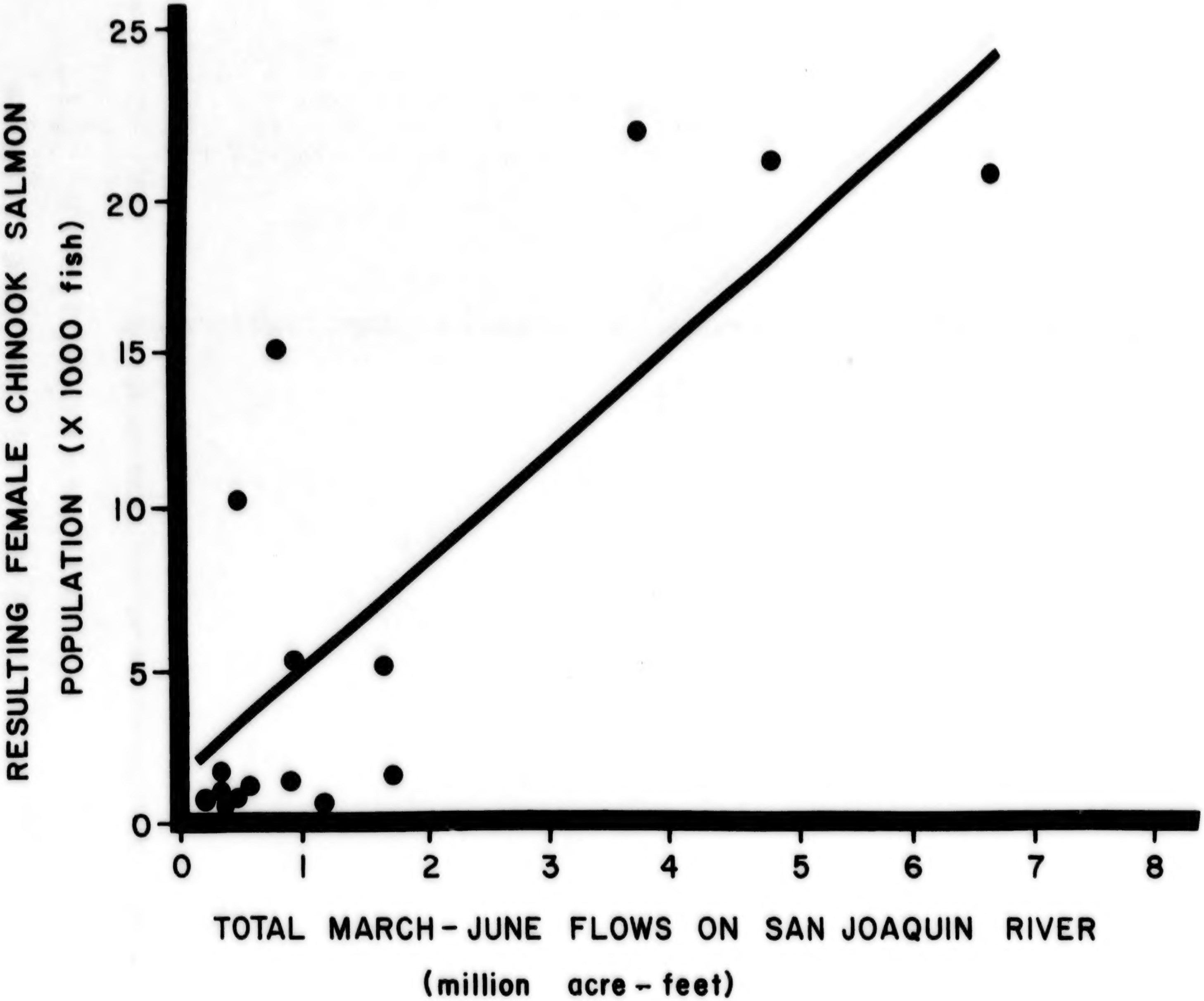

Figure 4. Relationship between the total March to June inflow of the San Joaguin River to the Sacramento-San Joaquin Delta (X) and the number of female chinook salmon spawning 2.5 years later (Y). Data is from the years 1957 to 1973. The regression equation is Y = 2.10 = + 0.004 X; r^2 = 0.689. 1 acre foot = 1.233 X 10^{-3} hectometers^3.

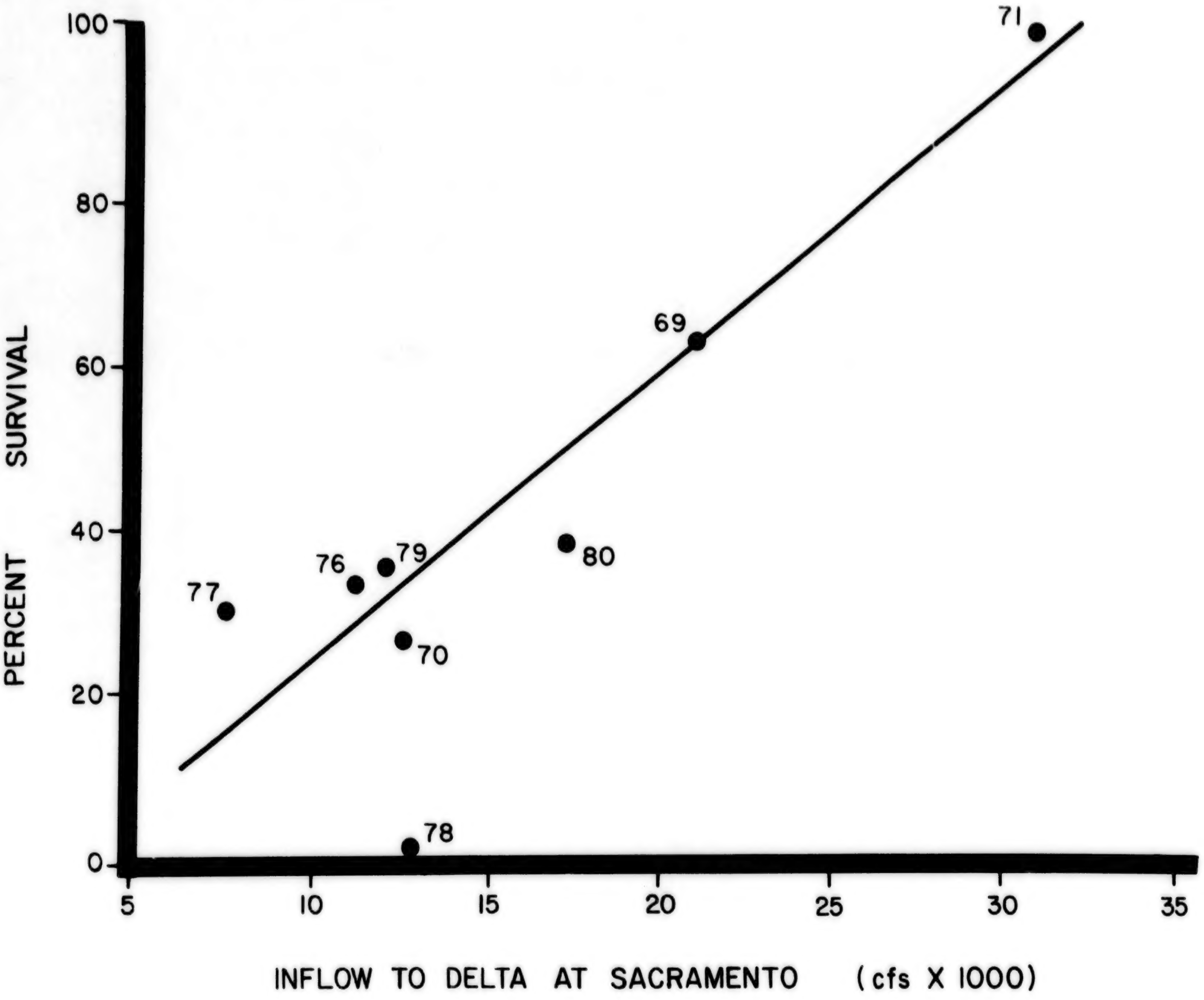

Figure 5. Relationship between spring (May or June) inflow to the Sacramento-San Joaquin River Delta at Sacramento (X) and estimated percent survival of marked juvenile chinook salmon as they migrate through the Delta (Y). Numbers adjacent to points indicate the years from 1969-1980. The regression equation is $Y = -0.137 + 0.000036 X$; $r^2 = 0.762$. 1 cfs = 0.03 m^3.

ocean CWT recoveries indicate survival of the control group released in Suisun Bay in 1978 was at least 100 times that of the fish released just above the delta (R. Menchen, CFG personal communication). Hence, conditions in the delta probably were more limiting to juvenile survival than conditions in the lower estuary. We plan to continue to estimate juvenile survival rates using the CWT technique.

ALTERATIONS IN THE DISTRIBUTION OF FRESHWATER FLOW

Juvenile Migration

The most direct evidence of alterations in delta flow patterns adversely impacting chinook salmon is the occurrence of young salmon at the State/Federal pumping plant fish screens. Records of salmon observed at the screens and respective spring export rates indicate that as exports increase more downstream migrating salmon are drawn to the screens. Before the State project began exporting water, mean monthly exports by the Federal project (CVP) (1959 to 1967) for April through June were 81 m^3/s (2,870 ft^3/s) with the mean total catch of salmon for the three months combined, about 113,000 fish. From 1968 to 1979 when both projects (CVP and SWP) were diverting, water exports and salmon collections increased to 132 m^3/s (4,670 ft^3/s) and 194,000 fish, repectively. The number of salmon observed at the fish screen probably represents less than 5 percent of the total downstream migration in the system (California Department of Fish and Game 1976), but a much larger fraction probably is drawn out of their normal migration path as will be discussed below. While many salmon are observed and counted at the fish screen collection facility, an additional 10 to 35 percent (dependent on size) are lost through the screens (Skinner 1974). Based on four yearly mark-recapture experiments, an average of 58 percent also are lost due to handling during the screen salvage process that returns fish to the lower delta out of the influence of the pumps (R. Menchen, CFG personal communication). In addition, mark-recapture studies indicated that approximately 96 percent of the juvenile salmon released in the forebay located just in front of the State project screen (Figure 1) are lost to predation (Hall 1980).

Additional, but poorly quantified, losses exist in the numerous agricultural, industrial and municipal diversions in the delta and upstream. Most of these are unscreened and together cause appreciable losses of salmon (Hallock and Van Woert 1959).

Fish screen studies in the Four Agency program include continued assessment of fish salvaged at the pumping plants in the south delta and a major effort to develop biological and engineering information required to plan, design, construct, operate and evaluate the Peripheral Canal intake diversion structure and associated fish screen facilities at Hood so as to result in the protection of fisheries exposed to that new diversion.

The alterations in flow distribution caused by drafting increased volumes of water across the delta to the pumps apparently increases mortality of salmon that do not ever reach the fish screens. In 1976, marked juvenile salmon were released in three areas in the northern delta to determine how survival of juveniles would be affected by the cross delta flow pattern. Recoveries were made by trawling in the western delta near Pittsburg. Results indicate that the highest survival (based on percent recovery) occured for fish released in the Sacramento River and Steamboat Slough system (Figure 6). These two channels represent the most direct route through the delta pumping. Fish released in the South Fork of the Mokelumne River (the eastern most route) had the lowest survival and least direct route through the delta and, along with those released in the North Fork of the Mokelumne River and Georgianna Slough, were on a direct path to the pumping plants. Recoveries were greater for the larger fish of a given release group suggesting that survival rate increases as the migrant size increases regardless of the path of migration.

Adult Migration

Adult migration through the estuary also has been affected by alteration of the delta flow patterns due to south delta pumping operations. Adult salmon are guided to their spawning grounds by olfactory perception of "homestream" water (Hasler 1960). Impacts on San Joaquin stocks were quantified by sonic tagging studies from 1964 to 1967 (Hallock et al. 1970). This work indicated that San Joaquin River spawners were prevented from using some channels normally used for migration due to flow reversals caused by water project pumping in the south delta.

ALTERATIONS IN THE QUALITY OF FRESHWATER FLOW

Limited information is available in the Sacramento-San Joaquin Estuary to document water quality related impacts on salmon that are associated with freshwater flow. High water temperature and low dissolved oxygen have been shown to adversely influence adult migrations in the San Joaquin near Stockton in the fall (Hallock et al. 1970). Salmon are reluctant to ascend the San Joaquin River near Stockton (Figure 1) when temperature exceeds 19°C (66°F) and are virtually stopped when dissolved oxygen drops below 5 mg/l. Generally the problem is relieved when inflow to the delta increases in late October or November. The low dissolved oxygen is due to high biological oxygen demand (BOD) most likely caused by high levels of organic materials from suspended organics in the river, sewage treatment plants, effluent discharges and agriculture return flows.

SUMMARY

This paper has provided a review of our current understanding of the influence of river inflow on chinook salmon in the Sacramento-San Joaquin River Estuary. As part of our discussion, we have described the methods used to gain this knowledge and developed hypotheses that link inflow to the survival, abundance, migration and rearing of salmon. We have presented evidence that the quantity, quality, distribution and timing of freshwater inflow in this estuary are potential factors that determine the survival of chinook in the Sacramento-San Joaquin River system.

Many of the present and potential flow-related problems for salmon are largely attributed to water development operations both upstream and within the estuary. Management plans have been designed to correct some of these problems.

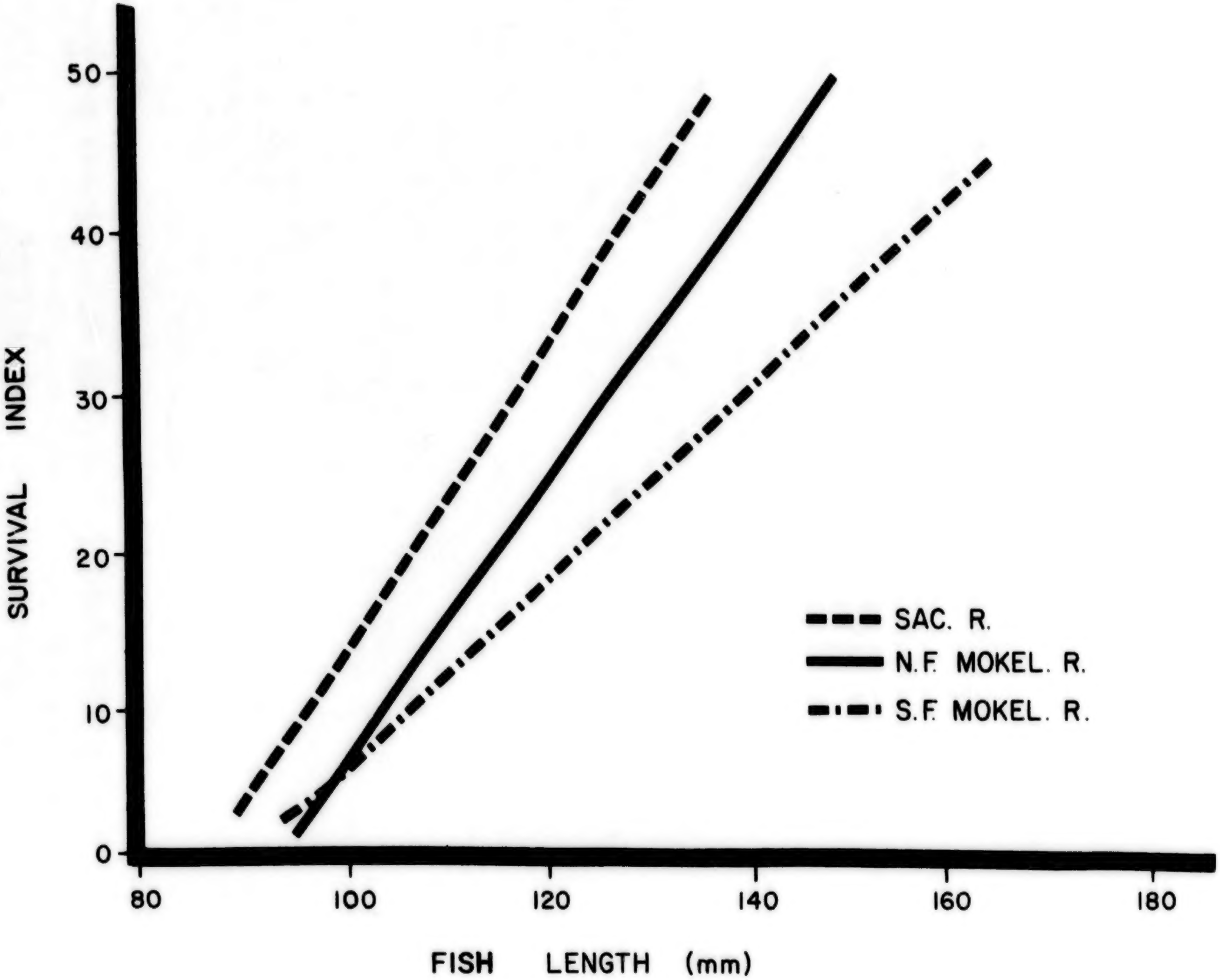

Figure 6. Relationship between percent survival index (Y) and size of marked juvenile chinook salmon released (X) at Sacramento River-Steamboat Slough (Sac. R.); North Fork Mokelumne River Georgianna Slough (N.F. Mokel. R.); and South Fork Mokelumne River (S.F. Mokel. R.) in the Sacramento-San Joaquin Delta. Survival indices are based on recovery of marked fish with a midwater trawl near Pittsburg during November, 1976. The regression equations for the Sacramento River-Steamboat Slough, North Fork Mokelumne River-Georgianna Slough and South Fork Mokelumne River locations are $Y = -0.447 + 0.0049 X$, $r^2 = 0.64$; $Y = -0.443 + 0.0045X$, $r^2 = 0.71$; $Y = -0.246 + 0.0027 X$, $r^2 = 0.77$, respectively.

One plan, the Peripheral Canal with associated fish screen facility, would potentially overcome present problems for salmon resulting from alterations in the distribution of flow. Conversely, there are unknown risks associated with the Peripheral Canal and related upstream storage reservoirs that may impact salmon adversely. Future management actions will attempt to understand these risks and take appropriate measures to lessen the impact on salmon.

Another management plan is to develop and utilize well documented and comprehensive flow standards that protect salmon while in the estuary. While present information indicates that by increasing inflow to the estuary at appropriate times we will see an increase in fry and juvenile abundance and juvenile survival, we do not know what this means for adult stocks. Unfortunately, the demand for water exceeds the supply. Hence, flow standards for salmon compete with other water management goals and they must be well documented.

Our approach to increase knowledge of salmon flow needs in the estuary includes: (1) mark-recapture studies using coded wire nose tags to document effects of varied conditions on salmon survival and to define the relative importance of estuarine rearing and (2) plans for long-term monitoring throughout the estuary since flow standards need to be based on replicate data sets collected over varied flow conditions. Continuous monitoring also is needed to verify present knowledge and to develop new information so that flow standards can be improved as environmental conditions and salmon populations change.

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DISCUSSION

Question: Terry Durkin, National Marine Fishery Service: Marty, I was listening to your comments on timing, and your juvenile chinook movements, and I'm just wondering if you might observe this data a little longer? Our experience on the Columbia is that the subyearling fall chinook seem to have a bimodal movement. One early movement, that could be associated with migratory movement is associated with high flows, that isn't related to that early flow. In some years you have early movement and in some years you have a late one, but it's not consistently associated with flow. They seem to be more related to time or sunlight or hours of the day than they do with the increased movement of water. So I suggest, maybe you might observe this situation on Sacramento a little longer.

Answer: I agree with you Terry. The main reason I brought up this data was to establish the point that you need freshets and high flow in the earlier part of the year to get fry into the estuary, This is necessary if they're going to use that system to attain substantial growth. Prior to smolting, the major smolt migration through the estuary is in May and June. It's much different in the Oregon and Washington area, apparently due to temperature and other things. Our delta gets high temperatures by July and August and we don't observe any juveniles in the Delta at that time.

Comment: Tommy Yokem, National Marine Fishery Service. One of the problems that we have in the San Francisco Bay estuary is not only finding what the freshwater needs are but also just how much fresh water there is coming into the system. According to John Conomos, historical outflow was about 30 million acre-feet and we are now down to about 21, and according to Perry, we are down to about half, or fifteen. If you talk to the Contra Costa County Water Agency, they say we're down to ten. And if you take what the Federal water project has as yield, it is about seven and a half million acre-feet. The State water project yield now is probably around 2 and a half million acre-feet, and according to the Department of Water Resources, those two projects are taking about forty percent of what's being taken out of the system. If you do some quick calculations, that says we are down to five million acre-feet from thirty. So there's a wide range of estimates of how much water is left in the system.

Question: Norm Benson, Fish and Wildlife Service: What's the relationship between the operation of the hatcheries upstream, freshwater inflow, and the release of fish?

Answer: You've raised a question. More information is certainly needed to evaluate the present and future hatchery releases, with timing, the size of release, where to release and so forth. Most of the state hatchery releases are made at Rio Vista in the spring while the Federal releases are still made upriver. Releases are made to parallel wild smolt outmigration and high flow when possible.

Some of the data I referred to on smolt survival as related to flow is based on a coded wire nose tag study we've been doing since 1978. Our initial results suggest they may have potential to impact hatchery operations and releases. We released 200,000 fish in the upstream spawning grounds on the Feather River, another 200,000 in each release group at Sacramento, and 200,000 as a control group at Port Chicago. Our initial returns from the adult fishery offshore show zero returns from our Feather River release, three from the Sacramento release, and approximately 1,300 from the Port Chicago release. That certainly indicates to me that they have a rough path to follow from upriver through the delta, probably for a variety of reasons. In the upper river you have temperature, diversion and predation problems, while in the delta proper you have water development problems as well as several others.

Question: Bill Davoren, Fish and Wildlife Service, Tiberon: I'd like to have you summarize for the non-Californians in the audience the status of the stocks of salmon on these two streams. Joel Hedgepeth, my favorite biologist/philospher, of all those types over age 60, last week suggested that maybe the striped bass which has been in the system 101 years now, is just getting fedup and tired and needs a dirtier river or something. It's just going to expire. Whereas the salmon, which has gone through a lot more than the striped-bass, due to its river origins, is hanging tough and may supplant the striped bass which at one time impacted its environment. I don't want you to comment on that, but could either you or Perry give us a brief status report on the stage of the stocks of the Sacramento and San Joaquin salmon compared to predevelopment?

Answer: As I said earlier the stocks have been decreased greatly. I believe in about 1953, the spawning stock estimate was about 600,000 salmon in the Central Valley and in 1967 it was about 180,000. The Sacramento had 200,000 and the San Joaquin about 3,000 in 1979. The San Joaquin drainage only has fall-run chinooks left. They've eliminated the spring-run chinook which was quite high in the San Joaquin drainage. Spawning escapement there runs less than five thousand right now and back in the 1940's it was about 150,000. Certainly we've lost quite a few, but considering some of the other systems in the Northwest there's still a lot of potential for chinook and we still appear to have more wild than hatchery fish. Hatchery operations and the fishery in other parts of the Northwest have apparently taken their toll on wildstock.

Question: Norm Benson, Fish and Wildlife Service, Slidell, LA: It was mentioned that to get water you are going to have to have well-documented beneficial uses to justify it or to get water rights. I know that there is some work being done in Fish and Wildlife, but is there someone taking a broad view on what beneficial uses exist?

Answer: Is your question, are people trying to identify what are benifical uses?

Question: Well, what are the things that can be used to justify getting water for the estuary. I know you have justified flow standards from the standpoint of striped bass and maybe marsh food production for waterfowl, but the beneficial use idea is a hazy concept. It involves a lot of things that haven't been reiterated here, and I just wondered what data are being collected or, how they are being addressed?

Answer: The concept is very complex. In California it's not so much a question of identifying beneficial uses as it is quantifying what's needed for those beneficial uses. The California State Water Resources Control Board recognizes a number of beneficial uses, and fish and wildlife resources is one of them. Problems arise when biologists have to come in with numerical estimates of what's necessary for fish and wildlife. For example, how many fish can we get back for an acre-foot of water? Such information must be available to hold up in court because you're going to be challenged by the other water interests every step of the way.

Comment: Tom Yocum, NMFS: We have a rough time coming up with comprehensive numbers. My own feeling for the San Francisco Bay system is that we desperately need the kind of information that Perry is generating. My own concern relates to the need for flexibility. What I mean, is there enough water left in the system? If Perry comes up with some recommendations for what the flow needs are for the San Francisco Bay, is that water going to be available?

Marty Kjelson: I agree with Tom, it gets down to two problems. One, you potentially have an over allocation of water already. Secondly, you have to prove the water needs that you're asking for. Often times, at least in the past, there's been no question that there was a beneficial use for agriculture and the requirements for growing crops, and so forth, were not questioned. But I support the California Water Resource Control Board in trying to initiate more sophisticated studies to document true agricultural needs rather than to simply give them a clean ticket and basically allocate all the water they want. They're finding that less water can be used on certain types of crops than was originally thought. So this is a step in the right direction. But it also gets down to priorities and tradeoffs. I think in most states, people's needs come first and the water for drinking is the top priority. Often in fisheries needs, we don't have all the data necessary to document the needs. We can show slides, such as the one I have up there. We may see a definite value in increasing flows to get a given survival rate, through the estuary, but there's all kinds of other factors influencing salmon stocks, such as harvest and spawning conditions. Before you know it, you have such a complex situation that you can't sort it out and quantify the needs simply. Sooner or later decisions have to be made. The priorities for fish and wildlife are often not very high.

You also can get "nickle and dimed" to death. A typical example is found in the San Joaquin Valley, where a contract for a large irrigation district has called for a 200,000 acre addition to their water allocation. Well, of course, the question was asked, "will that 200,000 acre-feet really hurt the fish and wildlife in the estuary? And of course you know that it is going to hurt, yet it will be difficult to quantify it given the variability that we have in biological systems.

Question: Well, picking up on what Marty said. Is there anything that can be done to insure adequate inflow into the estuaries? I hear that the flow has been reduced between 1900 and now by 50 percent. I also heard that in the next 20 years its going to be reduced another 50 percent, and I've heard people say that things are getting into a bad condition. Now what can be done about it? Does anybody have any suggestions?

Comment: Keith Bayha, Fish and Wildlife Service: I think the thing that needs to be done, is to get this society of ours away from trend-based planning for human population needs. Let's start work on a carrying capacity-based planning. The fact that everybody is struggling to get water to Southern California is ridiculous and the idea that down the road 20 to 50 years the population is going to continue to increase, simply is foolish. It boils down to looking at the country and saying how many people really can be maintained with the resources readily available in this area. Then you must tell the public through land use regulation or some other mechanism, that can't move into southern California until someone else moves out. In terms of what to do, I think we're going to have to do something that drastic.

The alternative is to sit back and let the economic planning people, who are educated to use trend-based planning for their projections to struggle like the dickens to meet those projections. We've got to turn that around and adopt some ecological concepts managing human populations.

Comment: Joe Mihurski, University of Maryland: Bill Davorern brought up Joel Hedgepeth's name, and reminded me of a poem that's pertinent to what the last gentleman was talking about. It goes like this:

Queen bee is a busy soul,
She has no time for birth control.
That's why in times like these,
There are so many sons of bees.

Just another brief comment. The problem in California is not so much one of people because we are led to believe that two-thirds of the people are living in the southern part of the State. Eighty-five percent of water use in California is for irrigated agriculture. Now, the people in the southern part of the State have the voting power. And if you want to talk about some people that have their act together in terms of a strong lobby, it's the agricultural people. One of the largest corporate farms in California is owned by the L.A. Times which also owns all of the cable T.V. in southern California. It's such a tangled mess of subsidies, and there's no ground water management. There's a water conservation program, agricultural water is highly subsidized, and water rights law is written in such a way that it encourages use. Conservation as originally defined the California water code is designed to prevent fresh-water from flowing into the ocean. And there are a lot of legislators that still believe that is what we are up against.

Comment: Terry Durkin, National Marine Fishery Service: I hope you can solve your problems in California. We certainly have comments about the advisability of taking Columbia River water and shipping it to California. Through the strength of our Northwest Senators, who have been in power for a number of years, this particular idea has been discounted quite often. However, they're not going to live forever nor even stay in office forever. The latest concept of withdrawing Columbia water for the starving Southwest is to take it out below Bonneville Dam. You see this way, our utility people will have their water going through the dams, but then because they don't really feel there's a use for water below the dam, they ship it down to the Southwest. And, of course, that would not really benefit our estuary at all. We

CHAPTER 10

GULF OF MEXICO FRESHWATER INFLOW EFFECTS

SOME EFFECTS OF FRESH WATER ON THE ATCHAFALAYA BAY SYSTEM

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ABSTRACT

Studies on marine animals caught in gill nets and trawls were conducted in 1974-1976 in the Atchafalaya Bay estuarine system, an increasingly important distributary of the Mississippi River. Comparison of the most distant bay from the river mouth, Vermilion, with Atchafalaya Bay showed replacement of the normal oligohaline estaurine fauna by a freshwater fauna during flood conditions in Atchafalaya Bay when salinity fell under about 0.5 ppt. A freshwater community of river shrimp, gars and blue catfish replaced a more typical estuarine fauna of white shrimp, anchovies and bull sharks. Reduced bay temperatures sometimes exceeding 5°C are suggested as a possible cause of an apparent decrease in productivity. It is suggested that temperature effects from floods may be significant influences on coastal systems and water management plans should consider such possible effects when designing flood systems.

INTRODUCTION

The largest floods entering estuarine systems in North America occur in Louisiana where the Mississippi River directly dumps into the Gulf of Mexico, but in recent years it has lost much of its water through a shorter route to the gulf, the Atchafalaya River. This flow is combined with that from the Red River to influence a large area of coastal water and, as a result, oyster production, as one example, has erratically but steadily moved away from the emerging Atchafalaya delta.

Historically oysters were produced in Atchafalaya Bay, but production over the last three decades or so has been in the gulf off Marsh Island, and in the last decade has begun a shift to the west of the mouth of Vermilion Bay, Southwest Pass. Because of the emerging delta in Atchafalaya Bay, the present study becomes historical, and some areas we worked in are now marsh.

In 1973 and again in 1975 large floods swept through the Atchafalaya system, affecting waters as far as 15 nautical miles offshore and 40 miles to the west, an area exceeding 800 square miles of gulf and bay waters. Peak flows at Morgan City on the Atchafalaya reached 700,000 cfs in 1973 and in 1975 exceeded 500,000 cfs. 1974 was not an especially low flow year, so salinities in the river's offing were low at the beginning of this study in September, 1974. For comparison, the Mississippi River near its mouth had a peak flow of over 1,200,000 cfs in 1973 and over 1,000,000 cfs in 1975.

The intent of this study was to consider what effects the increasing amounts of fresh water were having on Atchafalaya Bay, and since blue catfish (Ictalurus furcatus) are important members of very low salinity coastal waters, to pay particular attention to its role in the system. Results would then be utilized in developing a comprehensive management plan for the developing delta system.

Toward these ends comparisons were made between Atchafalaya Bay and Vermilion Bay, a higher salinity (oligohaline) area about 30 nautical miles to the west. Historically, Atchafalaya Bay probably had a similar salinity regime and there is evidence that Vermilion Bay salinities have also decreased somewhat in recent years. In any case, Vermilion Bay still produces a typical gulf estuarine fauna, whereas Atchafalaya Bay is turning into freshwater marsh and lakes, and during this study (1974-76) was usually fresh in salinity and fauna. Some attention was also paid to the intermediate areas of East and West Cote Blanche Bays and the immediate gulf areas off Vermilion and Atchafalaya Bays (Figure 1).

This paper is a summary of some data presented as a final report to the U.S. Fish and Wildlife Service in September 1976, "Study of sport and commercial fishes of the Atchafalaya Bay region." The report was reprinted with few changes in the "Atchafalaya Bay Fisheries Study" pages 89-129, in "A Progress Report, Fish, Wildlife and Related Resources Atchafalaya Basin, Louisiana," U.S. Department of the Interior, October 1979.

METHODS

For more details the original report may be consulted but basically there were two studies: (1) 24-hour monthly sampling with 200-foot experimental monofilament gill nets with equal amounts of 1-, 2-, 3-, and 4-inch mesh, two nets fished each in Vermilion and Atchafalaya bays from September 1974, through November 1975; and (2) collections with a 16-foot otter trawl, although begun in September 1974, expanded finally to monthly sampling at 13 stations (Figure 1). Concurrent hydrographic data were taken through the entire water column on salinity, temperature, oxygen, and turbidity.

All hydrographic data presented here represent surface conditions. Stratification was very rare except in the gulf during low flow periods and even there it was only significant on five occasions. In all statistical significances referred to in the text the probability of means overlapping is less than 0.5 according to a t test.

SALINITY

Salinity in Atchafalaya Bay remained below 0.1 ppt until June, not exceeding 0.5 ppt until August but then only sporadically, generally remaining 0.2 to 0.5 ppt from September 1975, through the conclusion of the study in March 1976.

In Vermilion Bay the salinity dipped below 1 ppt temporarily in November 1974, and in January through April 1975 but reached the low levels seen in Atchafalaya Bay only in April 1975. Highest salinity recorded was 9.3 ppt.

In the intermediate Cote Blanche bays, using a salinity of about 0.5

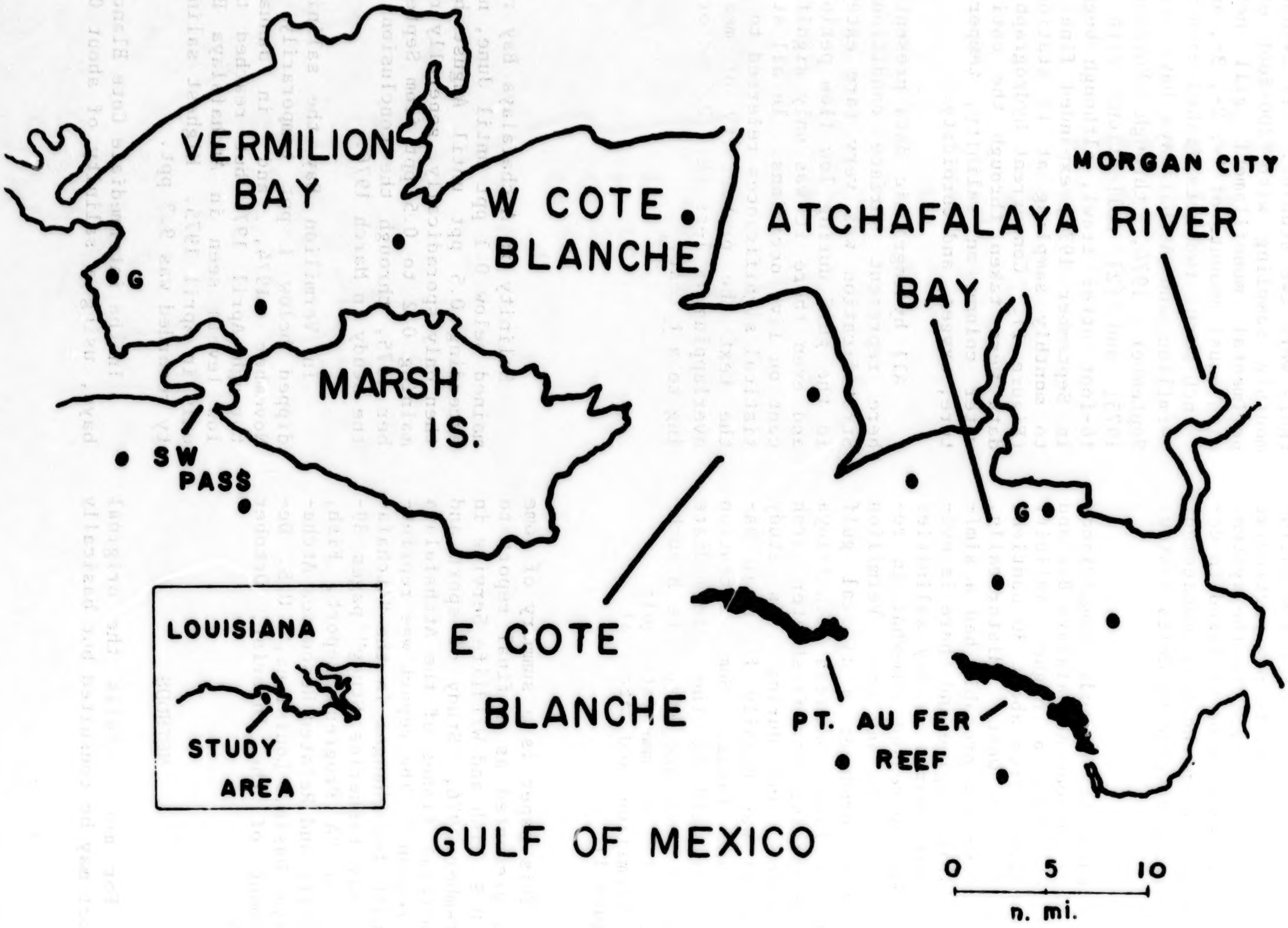

Figure 1. Study area trawl stations shown as dots. Gill net stations shown with "G".

ppt as the dividing line, flood conditions prevailed from December through August, and in East Cote Blanche especially, flooding remained very low through the end of the study.

In the gulf off Atchafalaya Bay regular sampling was not begun until flood conditions prevailed in April 1975, but generally salinities resembled those in Vermilion Bay, rising a little slower in July and August, but with occasional readings from 15 to 25 ppt thereafter.

In the gulf off Southwest Pass salinities were variable during the spring floods (0.3 to 13.5 ppt) but rose rapidly with cessation of flood waters, and while showing large fluctuations, consistently showed readings over 10 ppt, rarely reaching 24 ppt.

The evident pattern was that Atchafalaya Bay remained a very low salinity bay (less than 1 ppt) and during flood times essentially turned to fresh water. Vermilion Bay remained an oligohaline bay, with salinities of about 1 to 9 ppt, and during extreme flood times dropped below 1 ppt, but never turned into fresh water. The gulf off Atchafalaya Bay resembled Vermilion Bay and off Vermilion Bay was a typical estuary, except during flood times when it took the characteristics of the very low but not freshwater systems. (Table 1).

Some idea of the extent of coverage of low salinity waters can be gained from comparing Figures 2 and 3. Judging from inshore data and the turbidity most of the very dark water in Figure 2 represents very low salinity, whereas in Figure 3 salinities were probably estuarine across the same area.

TEMPERATURE

Temperature in shallow Gulf of Mexico estuaries and inshore waters generally follow air temperatures with some lag, but most obvious in Atchafalaya Bay was the dominance of flood water temperatures above air temperatures. Data were not specifically gathered to show temperature differences between the systems, so data for any given period were not always comparable, especially during the spring and fall when temperatures change rapidly.

Nevertheless, the effect was obvious as shown by the following facts: average water temperatures, taken for the main period hydrographic data, (Table 2) were significantly different between Atchafalaya and Vermilion Bays, but intermediate areas were not, although intermediate in values. The effects were most noticeable during winter and spring when river levels are highest and carrying the most water. In fact, temperatures were sometimes 5°C colder in Atchafalaya Bay and the differential in times of heavy flood was probably greater. Also, significant variations occurred in air and water temperature differences between the two bays (Table 3) in the winter and early spring of 1975-1976, the only period when consistent air temperature data were available. Average differences between daytime air and water temperatures in Vermilion Bay were less than 1°C, but were over 3°C in Atchafalaya Bay even though this period had less river flow than during the 1973 and 1975 floods.

Perhaps most important is the difference between air and water temperatures in each bay (Table 4). The differences were insignificant in Vermilion Bay and the adjacent gulf, but significant in all other areas. The greatest differences

Table 1. Summary of salinity (ppt) data by area.

	Vermilion Bay	West Cote Blanche	East Cote Blanche	Atch. Bay	Atch. Gulf	Vermilion Gulf
Mean	3.6	0.7	0.6	0.5	2.0	12.7
Standard deviation	3.16	0.6	0.59	0.78	2.07	2.7
Standard error	0.5	0.5	0.17	0.12	0.48	2.7
Number of samples	36	12	12	46	19	21
Range	0.2 to 9.3	0.2 to 4.0	0.2 to 2.2	0.1 to 0.9	0.1 to 6.1	0.3 to 19.8

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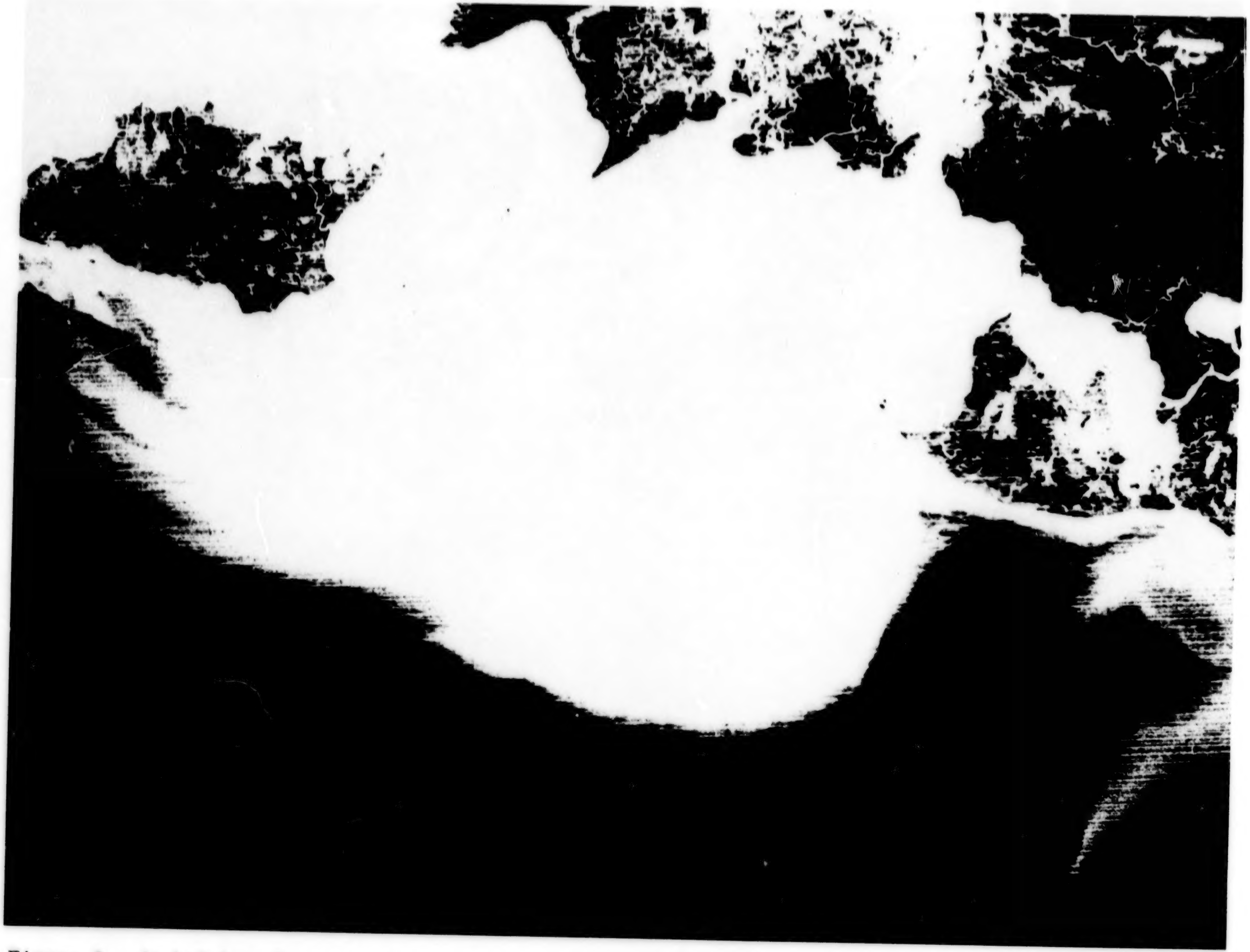

Figure 2. Atchafalaya Bay area from satellite, 16 April 1975.

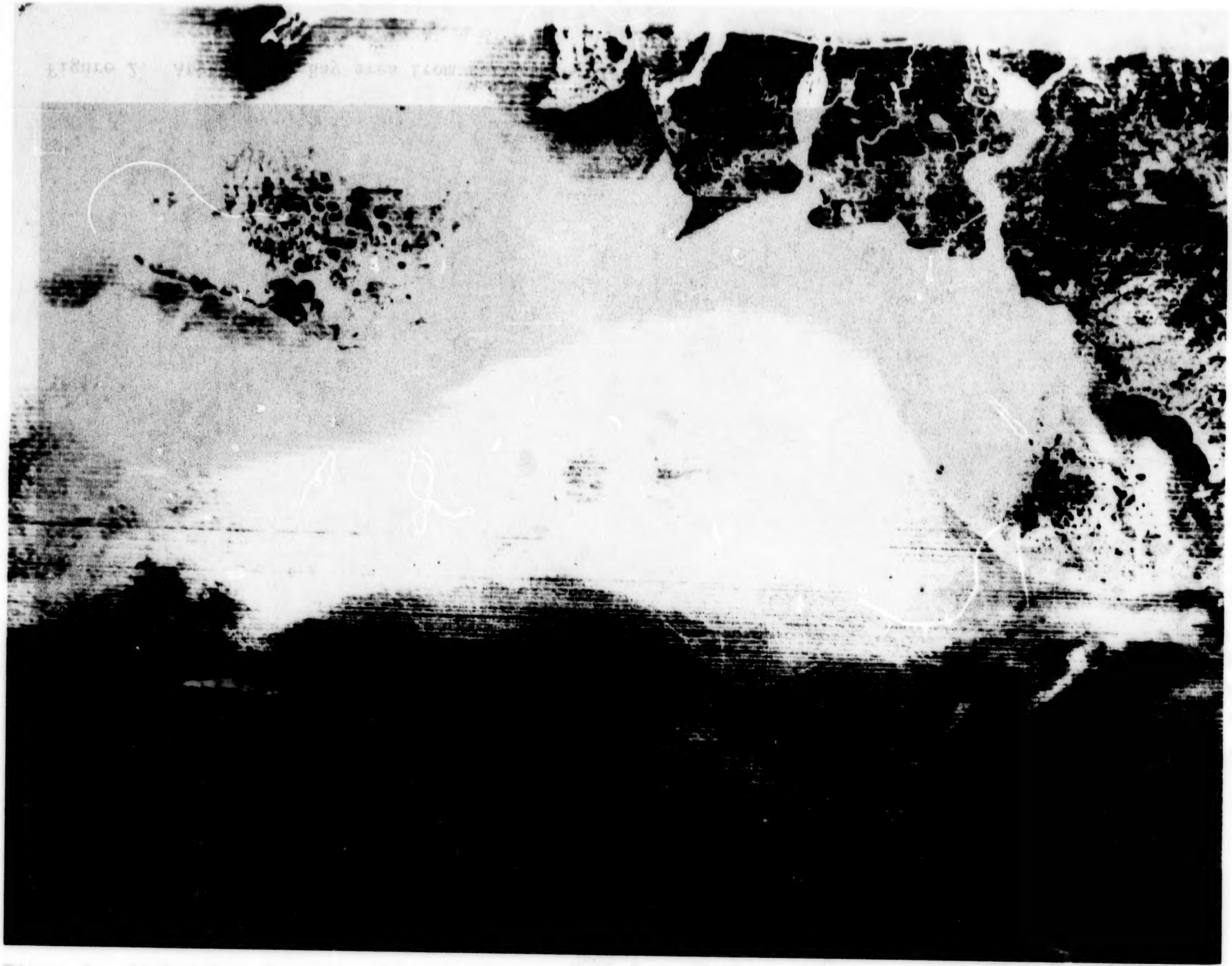

Figure 3. Atchafalaya Bay area, from satellite, 31 October 1975.

Table 3. Summary of water (W) and air (A) temperatures (°C) by area. VB=Vermilion Bay, E&WCB=East and West Cote Blanche Bay, AB=Atchafalaya Bay, AG=Atchafalaya Gulf, VG=Vermilion Gulf.

	VB		E&WCB		AB		AG		VG	
	W	A	W	A	W	A	W	A	W	A
Mean	14.86	15.78	12.21	13.75	11.18	14.13	13.3	16.08	14.87	15.28
Standard deviation	7.23	6.95	3.28	3.06	4.08	3.38	4.48	3.72	6.54	6.49
Standard error	1.87	1.93	1.04	0.97	0.91	0.78	1.83	1.52	2.07	2.05
Number of samples	15	15	10	10	20	19	6	6	10	10
Range	7.9 to 25.1	8.0 to 25.0	9.1 to 18.4	10.0 to 19.0	7.7 to 19.6	9.0 to 19.5	8.6 to 18.8	11.0 to 20.0	9.2 to 25.4	9.0 to 25.0

Table 2. Summary of temperature (°C) data by area.

	Vermilion Bay	West Cote Blanche	East Cote Blanche	Atch. Bay	Atch. Gulf	Vermilion Gulf
Mean	21.91	20.82	20.48	19.26	22.84	21.45
Standard deviation	7.87	8.54	8.93	8.55	8.33	7.99
Standard error	1.31	2.46	2.58	1.26	1.91	1.74
Number of samples	36	12	12	47	19	21
Range	7.7 to 30.2	9.1 to 30.4	9.2 to 33.2	6.7 to 31.3	8.9 to 34.5	9.2 to 30.1

Table 4. Summary of difference between air and water temperatures (°C), November 1975-March 1976.

	Vermilion Bay	E & W Cote Blanche	Atch. Bay	Atch. Gulf	Vermilion Gulf
Mean	0.85	1.77	3.08	2.78	0.46
Standard deviation	1.51	1.82	1.74	1.78	0.78
Standard error	0.4	0.57	0.4	0.73	0.25
Number of samples	15	10	19	6	10
Range	0.5 to 4.1	1.4 to 5.6	0.1 to 6.8	0.2 to 5.6	0.1 to 1.3

occurred in Atchafalaya Bay and the adjacent Gulf of Mexico.

THE FAUNA

There was a clear-cut difference between the animals caught in Vermilion and Atchafalaya Bays. Although this difference broke down somewhat in the summer and fall of 1975 when salinities rose throughout the area, Atchafalaya Bay was still distinct. Its community was characterized by river shrimp (Macrobrachium ohione) and blue catfish, while Vermilion Bay had large populations of white shrimp (Penaeus setiferus) and bay anchovy, (Anchoa mitchilli). A few species, such as gizzard shad (Dorosom cepedianum) and blue crabs (Callinectes bridged the gap somewhat.

But there were more differences than similarities in the major large predators such as bull sharks (Carcharhinus leucas) in Vermilion Bay and gars (Lepisosteus spatula and L. oculatus) in Atchafalaya Bay.

As evidenced by the total trawl catches (Table 5), Atchafalaya Bay contained fewer large individuals, mainly because of the predominance of large freshwater fishes such as the catfishes.

Vermilion Bay appeared to be a better estuarine nursery area with large populations of bay anchovies, white trout (Cynoscion arenarius) and the young of several other species.

Also gill net catches were larger in Vermilion Bay (Table 6), and were mainly made up of a large complement of estuarine species, including speckled trout (Cynoscion nebulosus) and sheepshead (Archosargus probatocephalus) which were rarely caught in Atchafalaya Bay.

DISCUSSION

The basic question is whether any particular management plan affects the basic productivity of the bay or simply shifts the system from one community type to another. There is no question that very low salinities (under 0.5 ppt) are limiting to the estuarine community dominants such as penaeid shrimps and anchovies. But, to some extent, these are replaced by freshwater types such as river shrimp and blue catfish. Some species may provide some overlap, but the general effect is well documented (Morton 1973). Regarding this effect, it may only be a matter of preference whether estuarine or a freshwater fauna is selected for. At least the decision is based on economics, not ecology.

An effect that may exist, however, is a diminution in productivity of either freshwater or estuarine fauna, from the influence of the cold Mississippi and Red rivers. Many marine organisms seem more affected by temperature than salinity within tolerance ranges. Those in the gulf show evidence of increased metabolism and growth at higher temperatures, while some evidence exists that temperatures of about 20°C or greater are necessary for efficiency (Eldred et al. 1961; Wohlschlag et al; 1968, Moore 1976).

Temperatures between 15 and 25°C occur in the spring at the same time the larvae and young of many species are inshore and at the same time of peak flood waters. If floods delay for 2 to 5 weeks temperatures exceeding 20°C, then a significant portion of the coastline may be taken

Table 5. Summary of total trawl catches by bay system.

	Number	Weight (g)	Number of collections
Vermilion Gulf	413.4	1426.2	19
Vermilion Bay	603.5	1389.6	22
East and West Cote Blanche Bays	390.5	2071.7	32
Atchafalaya Bay	138.5	2129.4	41
Atchafalaya Gulf	353.1	1928.8	17

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Table 6. Summary of gill net catches in total catch per hour per net.

	Atchafalaya Bay			Vermilion Bay		
	Number	Weight (g)	Temp. range (°C)	Number	Weight (g)	Temp. range (°C)
Sept.-Oct. 1974	1.7	938.8	21.8-27.1	4.0	3532.8	24.7-31.1
November 74-May 75	0.1	12.9	8.9-24.5	2.5	941.7	12.8-24.5
June-October 1975	9.5	1855.9	21.5-31.3	20.1	10,788.9	22.4-29.9
November 1975	0	0	12.3-14.5	2.5	964.5	24.8-25.1
Average	3.4	751.3		8.6	4600.9	

out of production for the young of many estuarine species. Workers in Louisiana have been studying temperature effects on brown shrimp since the 1973 flood (White 1975 and others), but most studies on floods emphasize salinity and nutrient effects.

The present study offers no conclusive proof, but some facts suggest production was slow in Atchafalaya Bay during the flood peak. (1) Collections by gill nets were negligible in Atchafalaya Bay during the peak flows, but trawl catches showed no such difference. Trawls catch stationary animals; gill nets capture those moving. Lack of movement may be the result of depressed metabolism. (2) Although the weight of trawl-caught animals (Table 5) in Atchafalaya Bay was high, the numbers were very low, suggesting exclusion of the nursery function.

There is a real possibility that any depression in growth is made up later due to fertilizing effects from the flood, but it is certain that the time cannot be made up. Since the depressed temperature effect from cold river water extends, albeit with diminished effect, into higher salinity areas, the production of many more species than just those in the fresh flood waters might be involved.

The difficult question to answer is to what extent flood control and other water management practices have affected coastal water temperatures. With the intent historically to move water seaward as rapidly as possible in narrow but deep channels, it would seem that practices have been selected for keeping seaward-moving water as cold as possible.

Although the present study was designed for other purposes it appears that the most important conclusion is that winter and spring floods are significant influences on coastal water temperatures. The importance of temperature to aquatic animals is well known, so it would seem important to examine in detail the effects and consider coastal temperature effects in water management policy. Spreading flood waters widely across deltas, the natural situation, would seem to be the best alternative for warming waters moving to the coast. Similar conclusions for handling flood waters were reached by Viosca (1928) and Gunter (1957) but for reasons other than temperature.

ACKNOWLEDGMENTS

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FRESHWATER INFLOW AND SALT WATER BARRIERS FOR MANAGEMENT OF COASTAL WILDLIFE AND PLANTS IN LOUISIANA

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ABSTRACT

The Louisiana coastal marsh is subdivided into four types: saline, brackish, intermediate, and fresh. The types occur in bands generally paralleling the coastline and contain characteristic water salinity levels and plant and animal communities. Intermediate and fresh types provide preferred habitat for most wildlife species and receive greatest use; salt marsh receives least use. Activities of man coupled with natural processes such as subsidence and erosion have removed any natural tidewater barriers and reduced freshwater flow through the marshes. As a result, saltwater intrusion from the Gulf of Mexico has increased, the boundaries of marsh types have been altered, and preferred habitat for many wildlife species has been reduced. As a corrective measure, marsh impoundments have been contructed on the Chenier Plain to serve as saltwater barriers and wildlife management units. Fresh water should be diverted from the Mississippi River into the marshes of the Inactive Delta Marsh Zone for reducing saltwater intrusion and building new marshland. The reestablishment of marsh types to their location in 1943 was recommended as a goal for marsh restoration.

INTRODUCTION

Population levels of wildlife species occupying wetlands are a product of the quality and quantity of the habitat available. Individual species have specific habitat requirements and greatest populations occur when conditions are within the optimum range. However, the rapid loss or modification of coastal wetlands, as a result of changing land use practices, has caused habitat conditions to deteriorate, plant communities to change, and wildlife populations to decline in many areas.

Activities which have had the most damaging impact on wildlife habitat are canal construction associated with oil and gas exploration, pipelines, navigation, and flood control; permanent drainage for agriculture, industry, and urbanization; modified drainage patterns associated with levee and highway construction and spoil deposits; and dredge and fill operations. The activities of man coupled with natural processes such as subsidence and erosion have greatly altered habitat conditions and thereby altered distributional patterns of plants and wildlife. Only with a complete understanding of the distributional patterns of plants and wildlife and the effects of environmental conditions can the magnitude of habitat changes be assessed and plans for altering conditions to maximize production be formulated.

DESCRIPTION OF THE COASTAL REGION

The coastal region of Louisiana can be divided into two segments on a basis of origin and physiography. The area east of Vermilion Bay and occupying two-thirds of the coastal region has been designated as the Deltaic Plain. The Deltaic Plain is composed of several distinct former deltas plus the present active delta of the Mississippi River. Marshes of the Deltaic Plain were termed the Active Delta Marsh Zone and Inactive Delta Marsh Zone by Chabreck (1970) for descriptive purposes. The area west of Vermilion Bay has been named the Chenier Plain and was formed from Mississippi River sediments swept westward by longshore currents in the Gulf of Mexico (Coleman 1966).

Marshes of the Louisiana coastal region encompass an area of approximately 1.7 million hectares and expand the full coastline of the State. The marshes extend inland for distances ranging from 24 to 80 km and reach their greatest width in southeastern Louisiana.

Water levels in these marshes are greatly affected by rainfall, tides and local drainage patterns. Water levels are typically within 30 cm of the marsh surface with exceptions occurring with storm tides or during periods of excessive rainfall or prolonged drought. The effects of tides are greater in areas nearer the Gulf of Mexico; however, tide levels in the gulf affect water drainage from interior marshes. In addition to its effect on marsh water levels, tidal action in the gulf also provides a source of highly saline water to the marshes. The daily fluctuating action causes highly saline waters to move inland and mix with advancing fresh water to form a vast estuarine basin. The mixing of salt water from the gulf and fresh water from inland sources provides a horizontal stratification of water salinities. Water salinities range from highly saline (20 to 25 ppt) near the coastline and gradually decline moving inland until a zone of fresh water is reached along the northern perimeter of the marsh region.

Penfound and Hathaway (1939) studied the coastal marsh in southeastern Louisiana and noted that water salinity and water depth were major factors governing plant species distribution. They subdivided the marsh into types on a basis of salt concentration of free soil water, designated these types as saline, brackish, slightly brackish (intermediate), and fresh, and described the plant associations within each type. The marsh types along the entire Louisiana coast were mapped by Chabreck et al. (1968) on a basis of the plant associations described by Penfound and Hathaway (1939). Chabreck (1972) then described the plant species composition and soil and water characteristics of each marsh type.

VARIATION AMONG MARSH TYPES

Marsh vegetational types along the Louisiana coast generally occur in bands paralleling the coastline. The marsh types are comprised of characteristic associations of plant species with similar salinity tolerances (Table 1).

Table 1. Plant species composition of the marsh types in the Louisiana Coastal Marshes[2].

Scientific Name	Colloquial Name	Vegetative Type			
		Saline	Brackish	Intermediate	Fresh
		Percent			
Batis maritima	Saltwort	4.41	0	0	0
Distichlis spicata	Saltgrass	14.27	13.32	.36	.13
Juncus roemerianus	Black rush	10.10	3.93	.72	.60
Spartina alterniflora	Smooth cordgrass	62.14	4.77	.86	0
Eleocharis parvula	Dwarf spikerush	0	2.46	.49	.54
Ruppia maritima	Widgeongrass	0	3.83	.64	0
Scirpus olneyi	Olney bulrush	0	4.97	3.26	.45
Scirpus robustus	Saltmarsh bulrush	.66	1.78	.68	0
Spartina patens	Marshhay cordgrass	5.99	55.22	34.01	3.74
Bacopa monnieri	Waterhyssop	0	.92	4.75	1.44
Cyperus odoratus	Flatsedge	0	.84	2.18	1.56
Echinochloa walteri	Walter's millet	0	.36	2.72	.77
Paspalum vaginatum	Seashore paspalum	0	1.38	4.46	.35
Phragmites communis	Roseau cane	0	.31	6.63	2.54
Alternanthera philoxeroides	Alligator weed	0	0	2.47	5.34
Eleocharis sp.	Spikerush	0	.82	3.28	10.74
Hydrocotyle umbellata	Pennywort	0	0	0	1.93
Panicum hemitomon	Maidencane	0	0	.76	25.62
Sagittaria falcata	Bulltongue	0	0	6.47	15.15
Other species		2.43	5.09	25.26	29.10
TOTAL		100.00	100.00	100.00	100.00

[a] Source of data: Chabreck (1970)

Table 2. Mean water salinity (ppt) and soil organic matter (O.M.) content (%) of vegetative types within marsh zones.

Marsh Zones	Marsh Types[a]			
	Saline	Brackish	Intermediate	Fresh
Active Delta				
Salinity	-	8.74	2.38	0.95
O.M.	-	24.63	22.60	6.96
Inactive Delta				
Salinity	18.25	9.93	4.45	1.21
O.M.	18.46	37.97	51.72	64.77
Chenier Plain				
Salinity	14.59	4.13	2.57	0.74
O.M.	6.50	18.57	22.95	34.26
Entire Coast				
Salinity	18.08	8.17	3.34	0.98
O.M.	17.46	31.18	33.92	52.01

[a] Data from Chabreck (1970).

SALINE MARSH

Saline marshes are nearest the shoreline of the Gulf of Mexico and subject to daily tidal fluctations. Salt marsh forms a narrow band in the Chenier Plain but is very extensive in the Deltaic Plain and the two regions combine to form a total salt marsh area of 270,000 ha (Chabreck 1970). Salt marsh of the Deltaic Plain is dissected by numerous embayments and tidal inlets and as a result is exposed to rapid and drastic tidal action. The shoreline of the Chenier Plain is fringed by an almost continuous beach deposit. The beach restricts intrusion of gulf waters and delays run-off of freshwater.

Water salinities average 18.0 ppt (range: 8.1 to 29.4 ppt), and soils have a lower organic content (mean: 17.5%) than types located further inland (Table 2). Vegetation within this type consists of few species. The species are salt tolerant and dominated by Spartina alterniflora, Distichlis spicata, and Juncus roemerianus (Table 1).

BRACKISH MARSH

Brackish marsh is farther removed from the influence of highly saline gulf waters than saline marsh but is still subject to daily tidal action. Brackish marsh is a major marsh type of coastal Louisiana and comprises 520,000 ha. Normal water depths exceed that of salt marsh and soils contain higher organic content (mean: 31.2%). Water salinities average 8.2 ppt (range: 1.0 to 18.4 ppt). This type characteristically contains numerous small bayous and lakes.

Brackish marsh contains more plant diversity than salt marsh but is dominated by two perennial grasses, Spartina patens and Distichlis spicat (Table 1). An important wildlife food plant of brackish marsh, Scirpus olneyi, grows best in tidal marsh free from excessive flooding, prolonged drought, and drastic salinity changes. However, the species is often crowded out by the dominant grasses, particularly Spartina patens.

INTERMEDIATE MARSH

Intermediate marsh lies inland from brackish marsh and occupies an area of 280,000 ha. The marsh receives some influence from tides and water salinities average 3.3 ppt (range: 0.5 to 8.3 ppt). Water levels are slightly higher than in brackish marsh, and soil organic content averages 33.9 percent. Plant species diversity is high and the area contains both halophytes and freshwater species used as food by a wide variety of herbivores. Spartina patens dominates the intermediate marsh as it does the brackish type, but to a lesser degree. Other common plants are Phragmites communis, Sagittaria falcata, and Bacopa monnieri (Table 1).

FRESH MARSH

Fresh marsh occupies the zone inland from the intermediate marsh and south of the Prairie formation and Mississippi River Alluvial Plain. In many areas fresh marsh is adjacent to or intermixed with forested wetlands (swamp). The fresh marsh type encompasses an area of 530,000 ha and is equal to brackish marsh in size.

The type is normally free from tidal influence and water salinities average only 1.0 ppt (range: 0.1 to 3.4 ppt). Because of slow drainage, water depth and soil organic content (mean: 52.0%) are greatest in fresh marsh. In some fresh marshes, soil organic matter content exceeds 80 percent and the substrate for plant growth is a floating organic mat, referred to as flotant by Russell (1942). This type also supports the greatest diversity of plants and contains many species which are preferred foods of wildlife. Dominant plants include Panicum hemitomon, Eleocharis spp., Sagittaria falcata, and Alternanthera philoxeroides.

WILDLIFE USE OF MARSH TYPES

The distribution and abundance of the many wildlife species of the coastal marsh display a strong affinity to marsh types. In some instances, a wildlife species may be attracted or supported in greater abundance because of plant species comprising the marsh type. Such is usually the case for herbivorous species such as the muskrat (Ondatra zibethicus) and nutria (Myocastor coypus). On the other hand, the abundance of a carnivorous species may be related to environmental conditions or prey species within a marsh type, rather than plant species present. Such is the case of American alligator (Alligator mississippiens) whose distribution in coastal marsh is governed to a large degree by water salinity. The following is a description of the relationship of selected wildlife species to marsh types.

WATERFOWL

In a review of waterfowl use of coastal marshes, Lynch (1967) noted that 40 or more species are involved and each has its own set of environmental requirements or tolerances. Most species have extensive ranges and utilize coastal environments only as winter residents or as fall and spring transients.

Duck use of fresh and brackish water impoundments on the Chenier Plain was monitored by Chabreck et al. (1974). They reported that the major factors affecting duck use were the types of vegetation present, water depth, and time of year. They also noted considerable variation among species in habitat selection.

In an effort to determine habitat preference of dabbling ducks, Palmisano (1972) related dabbling duck use in the Louisiana marshes to the marsh types delineated by Chabreck et al. (1968) (Table 3). The species of dabbling ducks consisted mainly of pintail, gadwall, American wigeon, mallard, mottled duck, shoveller, blue-winged teal, and green-winged teal.

A preference index was computed for each type by dividing the percentage of all ducks observed in a particular marsh type during aerial surveys by the percentage of the total area surveyed occupied by that type. A preference index greater than 1.0 indicated a positive preference or selection of a type and a value less than 1.0 indicated a negative preference or avoidance of a type (Table 3).

Salt marsh averaged 1.8 percent of the dabbling ducks observed and 13.0 percent of the habitat surveyed for a preference index of 0.14. The low index indicated that ducks generally avoid this marsh type. The absence of preferred plant foods and flooded marsh during the wintering season are probably responsible for

Table 3. Distribution of selected species of wildlife by marsh type in Louisiana coastal marsh.

Marsh[a] Type	Population Distribution (%)	Habitat Distribution (%)	Preference[b] Index
	Dabbling Ducks[c]		
Saline	1.8	13.0	0.14
Brackish	30.0	37.0	0.81
Intermediate	29.3	19.0	1.54
Fresh	38.9	31.0	1.25
	Muskrats[c]		
Saline	14.5	11.6	1.25
Brackish	72.5	36.2	2.00
Intermediate	8.7	20.3	0.43
Fresh	4.3	31.9	0.13
	Alligators[d]		
Saline	0.0	21.7	0.00
Brackish	31.9	30.6	1.04
Intermediate	33.7	16.5	2.04
Fresh	34.4	31.2	1.10

[a] Boundaries delineated by Chabreck et al. (1968)

[b] Preference index = $\frac{\text{Population distribution}}{\text{Habitat distribution}}$

[c] Data from Palmisano (1972)

[d] Data from McNease and Joanen (1978)

low use. Also, ponds in salt marsh contain few aquatic plants (Chabreck 1971).

Brackish marsh contained 30.0 percent of the dabbling ducks and 37.0 percent of the habitat sampled. The preference index of 0.81 suggests that duck use was slightly below habitat availability and reflected duck avoidance. However, duck use was much greater than in salt marsh. Highest use of brackish marsh was in the fall and spring seasons when widgeongrass (Ruppia maritima) was available. A similar situation was noted by Chabreck et al. (1974) during their studies of marsh impoundments.

Intermediate marsh exhibited the greatest duck preference index (1.54) of the marsh types surveyed. This type made up only 19.0 percent of the habitat surveyed but contained 29.3 percent of the dabbling ducks (Palmisano 1972). The major factors attracting dabbling ducks to intermediate marsh were favorable water depths and abundant plant foods. Fresh marsh contained 38.9 percent of the dabbling ducks surveyed and comprised 31.0 percent of the habitat. The preference index of 1.25 indicated that ducks selected the habitat over the brackish or salt marsh types. Palmisano (1972) observed that dabbling duck use of fresh marsh was least during the fall and greatest during the winter. Chabreck et al. (1974) noted a similar situation and concluded that use increased in winter as seeds of annual grasses and sedges were deposited on the marsh floor and rising water levels improved feeding conditions.

MUSKRATS

Suitable habitat for muskrats must have adequate food plants, satisfactory amounts of water, and adequate denning sites for rearing young and escaping predators. Population level usually reflects the degree to which a particular area meets requirements of the species and may fluctuate drastically in response to short-term environmental changes.

Waterfowl are highly mobile and are able to move about freely in coastal marshes in search of preferred habitat conditions. Muskrats, however, are more sedentary and move less freely from one marsh type to the next. Muskrats are monogamous, and a mated pair in coastal marsh will construct a grassy house or lodge and remain in the vicinity of the house. Catastrophic events such as drastic flooding, drought, or other disturbances are usually required to cause movement from an area.

Because each mated pair of muskrats will construct a house, the number of active lodges in an area is indicative of the muskrat population size in the area (O'Neil 1949). The houses are very conspicuous and can be counted from aircraft.

Palmisano (1972) inventoried muskrat houses along transects of the Louisiana coastal marsh and tabulated the number of houses according to the marsh types identified by Chabreck et al. (1968) (Table 3). A productivity index was computed for each type by dividing the percentage of all muskrat houses observed in a particular type by the percentage of the total area surveyed occupied by that type. The productivity index was similar to the preference index computed for dabbling ducks and can be interpreted similarly.

Muskrats occurred in all marsh types; however, population densities varied greatly. The brackish marsh type composed of a mixed community of Scirpus olneyi and Spartina patens produced the greatest muskrat density, based on house counts (Palmisano 1972). Brackish marsh comprised 36.2 percent of the area surveyed and contained 72.5 percent of the muskrat occurred in brackish marsh at twice average density of all marsh types.

Salt marsh made up 11.6 percent of the area inventoried and contained 14.5 percent of the muskrat houses observed. The productivity index for salt marsh was 1.25 and indicated that muskrat productivity was greater than the coastwide average, but considerably less than brackish marsh. Although salt marsh often contains satisfactory populations of muskrats, the harvest is usually very low because of access problems in winter and low fur quality in that type.

Intermediate marsh comprised 20.3 percent of the area surveyed and contained 8.7 percent of the muskrat houses. Fresh marsh made up a larger portion of the area (37.9%) but contained only 4.3 percent of the muskrat houses. The low productivity indices for intermediate and fresh marshes (0.43 and 0.13; respectively) indicate that these types do not meet the overall requirements of muskrats. Inadequate water levels, food supplies, and cover are likely contributors to the low population levels.

NUTRIA

For many years the muskrat was the major species in the Louisiana fur harvest, but in the early 1960's the nutria (Myocastor coypus) replaced the muskrat and has remained the leader since then. Population density data are not available for nutria, but Palmisano (1972) used harvest rates as an indication of abundance and reported that catches declined as salinity increased. Harvest rates per 1,000 ha by marsh type were: fresh - 1266, intermediate - 704, and brackish - 213. Harvest data were not available for salt marsh but populations are generally lowest in that type.

ALLIGATORS

Alligators are widely distributed across the Louisiana coast and occur in practically all areas offering suitable habitat conditions and protection. Adult females inhabit secluded areas in marsh, construct subsurface dens, and seldom venture far from the den (Chabreck 1965; Joanen and McNease 1970). They nest in the vicinity of the den and the young produced remain in the area for one to two years. By the third year, the young begin to move about quite freely in response to water conditions and food availability. Movement continues over a period of five to six years and during that time the immature alligators are able to select from a wide variety of habitat conditions. As sexual maturity approaches in the ninth year, females begin selecting denning sites in remote marsh areas. Males continue to travel about over a large area (Joanen and McNease 1972) but during the courtship and breeding seasons remain in the areas selected by adult females.

A newly constructed nest of an alligator is very conspicuous from the air and serves as the basis of an alligator census method developed by Chabreck (1966). The census method requires flying low altitude aerial transects of marsh and counting the nests within a predetermined distance from the transect. The number of alligator nests within a marsh type is indicative of the alligator population of the type.

McNease and Joanen (1978) used the nest count procedure to inventory alligator nests along the Louisiana coast in 1977 (Table 3). During the inventory, 51 north-south transects were flown and nests observed were tabulated by marsh type.

Previous observations revealed that alligators do not use the saline marsh type; consequently, that type was not surveyed by McNease and Joanen (1978). The nest survey was expanded to project the total alligator population in the coastal marshes, as suggested by Chabreck (1966). The projection disclosed a total population of 174,000 alligators in the brackish, intermediate and brackish marsh types.

Brackish marsh comprised 30.6 percent of the coastal marsh and contained 31.9 percent of the alligator nests. The preference index of 1.04 indicates a use slightly greater than availability. Intermediate marsh contained only 16.5 percent of the marsh area but contained 33.7 percent of the alligator population. The preferences index was 2.04 and indicated a strong preference for the type. Fresh marsh was similar to brackish marsh and contained 31.2 percent of the area and 34.4 percent of the habitat. The preference index of fresh marsh was 1.10.

COASTAL ALTERATIONS

Stratification of the Louisiana coastal marshes into distinct marsh types has been maintained naturally by surface features and hydrological processes. The inland advancement of saline gulf waters was usually restricted by natural barriers such as beaches, cheniers, low marsh ridges, and natural levees along streams and lakes. The meandering and shallowing of coastal streams as they moved inland reduced their capacity to carry large volumes of salt water. Also, the discharge of fresh water from inland sources through coastal streams served to dilute and prevent the inland advancement of saline tide waters. During drought periods, when the freshwater flow through streams was reduced, many streams emptying into the gulf on the Chenier Plain closed off naturally at the beach, thus providing a natural barrier to tide water intrusion.

The activities of man including leveeing, canal dredging, and stream channelization coupled with natural processes such as subsidence and erosion, have reduced the effectiveness of saltwater barriers and altered hydrological process. Canals and channelized streams which connect tidal saline water sources to inland marshes of lower salinity function in two ways to alter marsh types. During low tides in the gulf, the canals flush fresher water from interior marshes and cause lower water levels. Then, with high tides in the gulf, saline water is able to move in a more direct route farther inland. The process is gradual, and a period of several years may be necessary for the effects to become evident.

As water salinity increases in the area, plants unable to tolerate the higher salinity die and are gradually replaced by species adapted to the new salinity regimes. Similarly, wildlife occupying the marsh type because of preference, seek out new areas. Populations of other species of wildlife may simply adjust to the productivity of the new habitat.

Greatest damage to plants and wildlife takes place when fresh marsh containing high levels of soil organic matter is subjected to much greater water salinity and strong tidal action. Plants in the area are killed by increased water salinity, and the organic substrate becomes loose and disorganized without plant roots to hold it together. As tide water moves through the area, small amounts of organic matter are carried and flushed out through tidal channels. Before new species can become established, marsh elevations may drop 10 to 20 cm over broad areas. Open ponds and lakes thus develop and productive marshland is lost. Thousands of hectares of marsh in the Inactive Delta Marsh Zone have been thus affected. The chances of such marsh again supporting emergent plant growth is very low unless corrective action is taken by marsh managers.

Prior to levee construction along the Mississippi River, overbank flooding would send vast quantities of fresh water and alluvium down former channels of the river and other streams emptying into the gulf on the Deltaic Plain. In many areas flood water from the Mississippi River would reach the gulf via sheet flow over the marshes.

As a result of overbank flooding, a tremendous area of fresh marsh was developed and maintained. Also, nutrient rich sediment was added to the marsh, thus enhancing productivity and promoting land building.

Because of several disastrous floods, the Mississippi River Commission was formed in 1879 and levee construction began in 1882. Completion of the levee system required many years, but today the levee system extends southward to the Active Delta (approximately 100 km south of New Orleans). Approximately one-third of the Mississippi River flow is diverted through the Atchafalaya River during flood stage. The remainder is carried through the leveed channel of the Mississippi to the Gulf of Mexico.

As a result of coastal alteration over the past half century, the location of marsh types in the Inactive Delta has changed considerably. Chabreck (1970) determined that the northern boundary of the salt marsh type had moved inland an average distance of 3.4 km during the 25-year period from 1943 to 1968. Encroachment of the salt marsh type was determined by comparing the location of the marsh type on a map prepared by O'Neil (1949) with its location on a later map prepared by Chabreck et al. (1968).

PROTECTION AND REESTABLISHMENT OF MARSH TYPES

Marsh management for wildlife is usually aimed at species with sport or commercial value. Along the Louisiana coast, these groups consist mainly of waterfowl, fur animals and alligators. Marsh management involves protection or establishment of marsh types which are most attractive or productive for the desired species; however, habitat improvement for one group usually benefits other wildlife also.

Previous studies on wildlife distribution show that greatest population levels occur in fresh and intermediate marshes (Table 3). The muskrat was the only species reaching greatest density in brackish marsh. Salt marsh generally contains lowest wildlife populations; consequently, the increased saltwater intrusion in recent years has resulted in a reduction of quality wildlife habitat.

Two procedures are generally used to prevent the inland encroachment of highly saline tide water. One method involves the construction of artificial saltwater barriers, and impoundments have been used for this purpose on the Chenier Plain for 30 years (Chabreck 1960). The other method involves freshwater introduction into the headwaters of drainage basins leading to the Gulf of Mexico. Fresh water moving through the basin dilutes the salt water and also adds inorganic sediment to the substrate. Several small-scale freshwater introduction projects have been completed in recent years and permit introduction of Mississippi River water into areas east of the river.

Impoundments are constructed by completely enclosing an area with a levee system. This procedure can be used only in marshes containing soils capable of supporting levees; consequently, its use is limited mostly to the Chenier Plain. Marsh soils in the Inactive Delta consist largely of organic matter and are generally unsuitable for construction of continuous levee systems.

Freshwater introduction into marshes, however, is limited to the Inactive Delta because of its proximity to the Mississippi River. The location of the Chenier Plain makes it inaccessible to introduce water from the Mississippi River. Also, water from the Mermentau River and several large lakes along the northern edge of the Chenier Plain are held in a basin for rice irrigation, thus reducing their use for freshwater introduction.

The use of marsh impoundments for management of coastal wildlife resources has been the subject of several studies (Chabreck 1960; Baldwin 1967; Chabreck et al. 1974; Morgan et al. 1975). Impoundments provide a means for controlling water salinity and water depth in a marsh to produce desired species of vegetation. However, levee systems used as barriers to saltwater intrusion also block the movements of marine organism in tidal channels and reduce the discharge of plant detritus into estuarine systems (Chabreck 1980).

Freshwater introduction into marshes of the Inactive Delta Marsh Zone has been long considered as a means for reducing saltwater intrusion and building new marshland through controlled deposition of sediments. In order to maximize wildlife and fisheries production in the Louisiana coastal region, a recommendation was made by an Interagency Study Group to reestablish the location of the salt marsh type to its 1943 position (U.S. Army Engineer District, New Orleans, Chairman of the Interagency Study Group 1970). The position of marsh types in 1943, as delineated by O'Neil (1949), was several kilometers south of their present position. Reestablishing marsh types to that position would require introduction of Mississippi River water in great quantities and at strategic locations. Gagliano et al. (1971) conducted detailed studies of the area and recommended discharge sites and rates. However, numerous political problems must be overcome before an effective plan can be executed.

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ESTABLISHMENT OF CONTROLLED FRESHWATER DIVERSIONS OF THE MISSISSIPPI RIVER INTO THE LOUISIANA COASTAL ZONE

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ABSTRACT

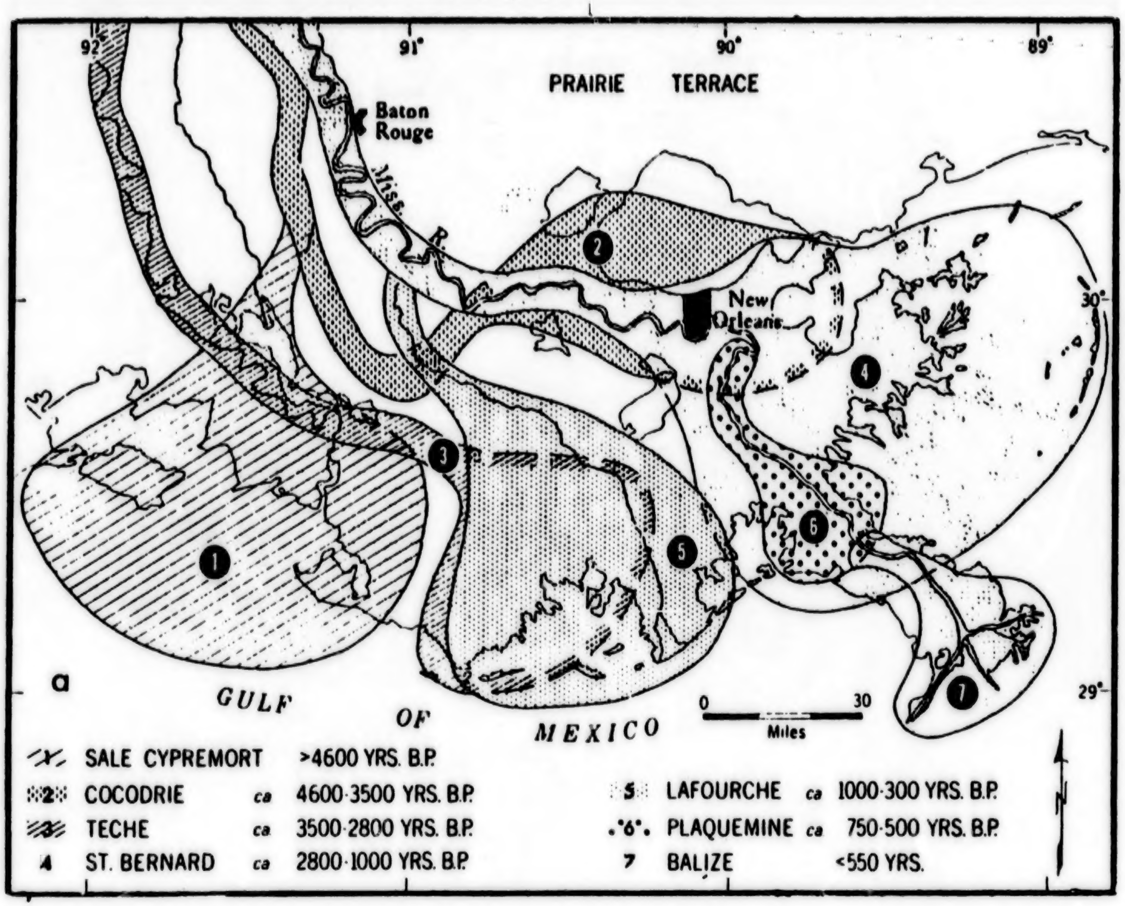
Land loss is the greatest environmental problem facing coastal Louisiana today. Erosion and subsidence are occurring at ever increasing rates and remain unchecked. Unless positive measures are taken to counter balance these deteriorating processes, the highly productive coastal wetlands are doomed to eventual destruction. Regulations of activities in the coastal zone can only retard man's aggravation of the deterioration process. Only a return to or a mimicking of the natural processes that occurred before man's intervention into the system can assure continued productivity of the area. Small scale freshwater diversions that address local area problems are the best first step in achieving the State's long range freshwater input plans. Successful small scale diversions will help alleviate many of the institutional problems associated with these projects.

INTRODUCTION

Louisiana's vast coastal wetland area, estimated at 25 percent of the coastal wetland area of the United States, was formed by the cyclic migration of the channel of the Mississippi River. Over the past 7,000 years, seven major delta lobes have formed due to the riverine input of water and sediments into the shallow waters of the Gulf of Mexico (Figure 1). The natural cycle was one of progradation and aggradation, abandonment and gradual degradation of the delta lobe. Degradation results from a combination of natural erosion by marine process and natural subsidence which is characteristic of the area. As this cycle continued uninterrupted, the balance between loss and gain was maintained and the system supported one of the most productive areas in the world.

In 1928, the U.S. Army Corps of Engineers began leveeing off the Mississippi River as part of the flood control measures in Louisiana. In addition, the construction of the Old River control structure near Morganza has prevented, at least temporarily, the migration of the river to a new route down the Atchafalaya basin.

All these measures have resulted in curtailment of riverine freshwater and sediment input into the wetlands of southern Louisiana. Several severe problems have resulted from these actions.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2 COCODRIE ca 4600-3500 YRS. B.P.
3 TECHE ca 3500-2800 YRS. B.P.
4 ST. BERNARD ca 2800-1000 YRS. B.P.
5 LAFOURCHE ca 1000-300 YRS. B.P.
6 PLAQUEMINE ca 750-500 YRS. B.P.
7 BALIZE <550 YRS.

Figure 1. Chronology and locations of delta lobes composing the Mississippi River deltaic plain (from Morgan 1970).

Maintenance of the current channel has resulted in the Mississippi River depositing its sediment load into the deeper waters of the Gulf of Mexico. The sediments traditionally deposited on the wetlands and in the shallower bay areas are no longer available for delta building. Natural subsidence and erosion are now unchecked and net land loss has resulted.

In the absence of freshwater introducton at the upper ends of the hydrologic basins, higher salinity water has intruded into the estuaries. This intrusion has been facilitated by the many canals that have been dredged in connection with oil and gas operations and navigation in coastal Louisiana. Saltwater intrusion into the brackish marsh and fresh swamp areas in the upper basins has resulted in dieoffs of the plant species intolerant of the higher salinities. The elimination of vegetation in these areas has allowed dramatic increases in erosion rates. The decrease in wetland area allowed larger volumes of water to move during each tidal cycle. Channels in the barrier islands and wetlands are scoured more, which allows increased saltwater intrusion.

Thus, the system contains a positive feedback loop leading to increasing land loss. Figure 2 is a simplified schematic showing the more important processess affecting the land loss in Louisiana's coastal zone. All of these factors, including man's activities, has resulted in a net loss of approximately 16.5 mi^2 (26.5 km^2) annually of coastal wetland area (Gagliano and Van Beek 1970).

LOUISIANA COASTAL PROGRAM

The genesis of Louisiana's coastal resource program began with the identification of the major problems in the coastal zone. Among the problems recognized, land loss was of major importance because wetland area has been shown to be tied to fisheries productivity (Figure 3), (Craig et al. 1977). In order to maintain this valuable renewable resource, it is necessary to address this critical problem.

Louisiana's management program approaches these problems in two distinct ways. The first approach is regulation. Guidelines were established to regulate uses of the coastal zone and prevent or minimize the aggravation of the natural deterioration process through man's activities. Regulation will hopefully retard the rapid deterioration of Louisiana's wetlands.

The second and most important approach is the implementation of programs designed to restore or mimic the natural processes which were acting before man's intervention into the system. These programs will address the basic causes of wetland deterioration, sediment starvation and saltwater intrusion.

Early studies done in Louisiana recognized the possibilities of freshwater diversions in alleviating these problems in coastal areas. Gagliano et al. (1971) explored both water and sediment diversions of the Mississippi River to combat wetland deterioration. Utilizing a broad approach to the problem, they identified potential diversion sites and calculated water requirements to

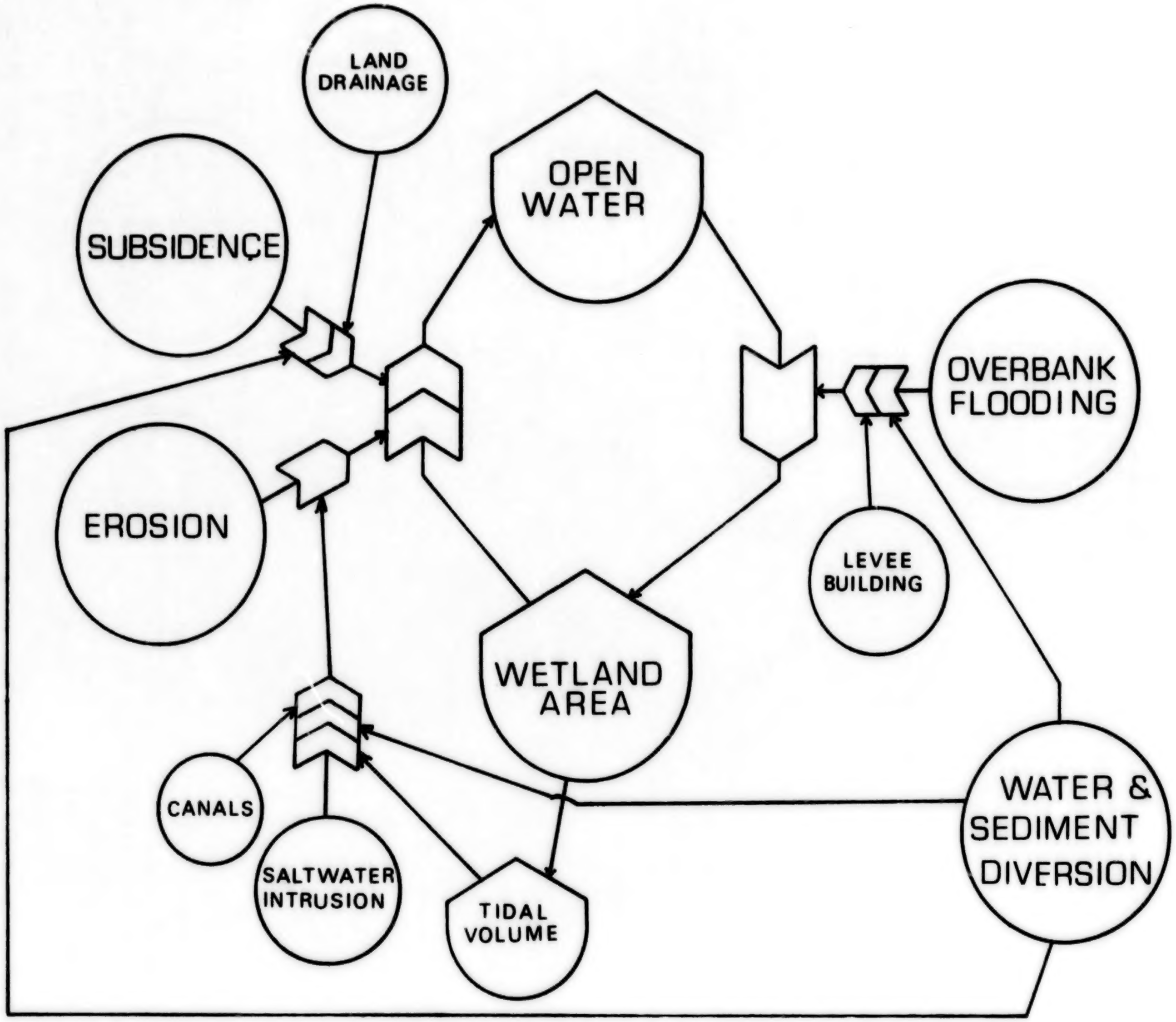

Figure 2. Schematic showing the major processes governing land loss and deposition in the Mississippi Delta Plain.

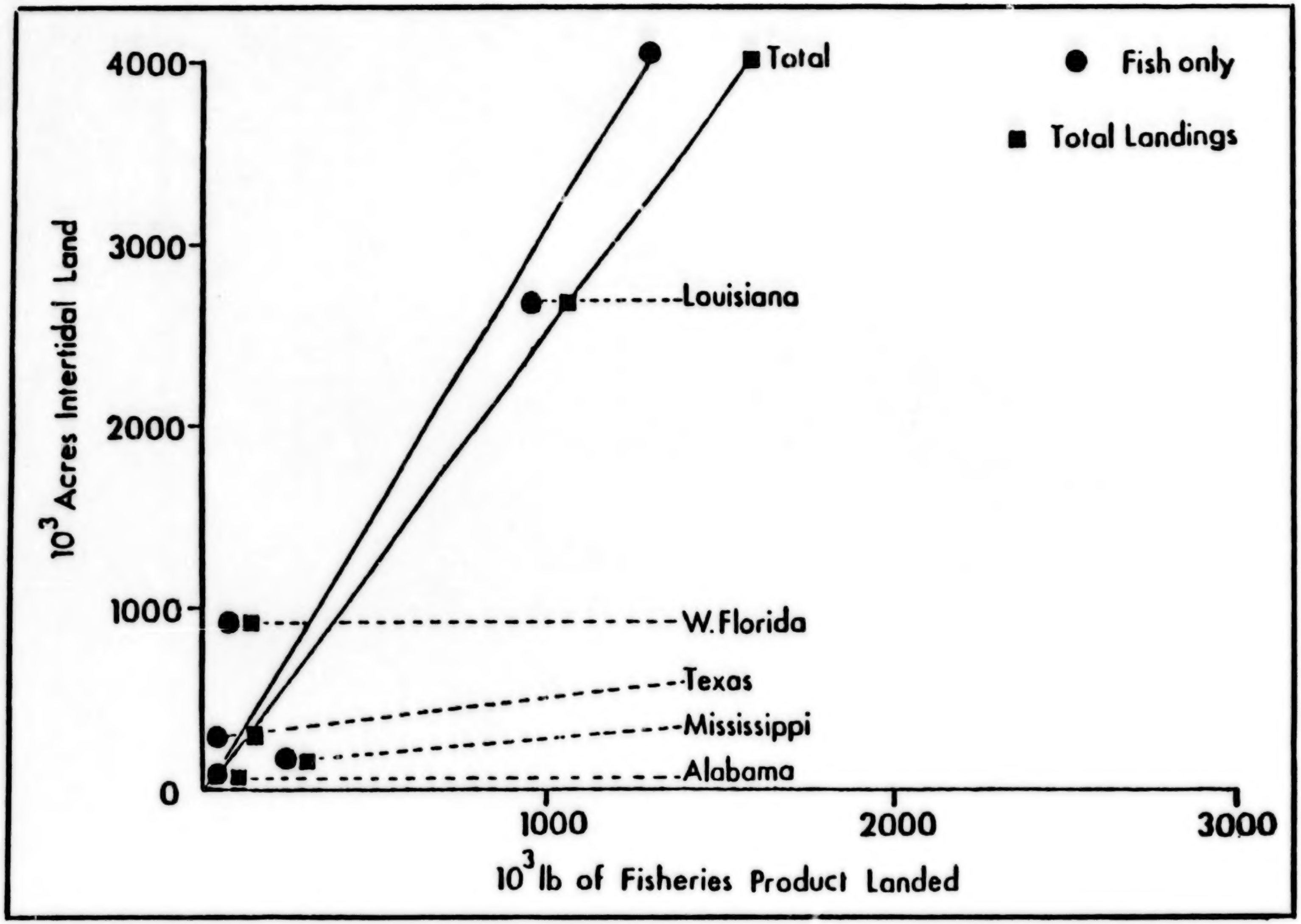

Figure 3. Relationship between fisheries yields and intertidal areas for the Gulf of Mexico (from Craig et al. 1977).

maintain 15 ppt isohalines in designated areas in the various hydrologic basins. This report forms the basis for the U.S. Army Corps of Engineers' plans to construct large scale freshwater diversions (1,000 to 6,000 cfs). These plans are currently in the research and development stage and are not foreseen in the near future.

The Louisiana coastal resources program's interest in freshwater diversion began in 1978 with the passage of the Louisiana Coastal Zone Management Act. In the Act, the legislature recognized the problems of coastal Louisiana and mandated our department to formulate a freshwater diversion plan for Louisiana.

The Louisiana coastal resources program has recognized two levels of implementation of freshwater diversions. The first is the large scale diversions which will affect salinity and hydrology on a basinwide scale. These are the types of projects currently being studied by the Corps of Engineers. Due to the huge cost and long range planning of these large diversions, we feel that diversions of this scale should be a joint-coordinated project between the State and Federal Government. Efforts toward implementation of these projects will continue.

The second level of implementation is small scale diversions designed to alleviate problems at the local level. Our initial emphasis will be at this level for several reasons.

The types of diversions are affordable at the State level. Various funding sources at the State level, including coastal energy impact program and 306 grant funds, can be used to construct and monitor these smaller diversions.

Small scale diversions can be planned and constructed in a relatively short time frame. Optimistic time frames for the large diversions planned by the Corps show completion in the early 1990's. Small scale projects can be planned and constructed in three to five years as models for the larger scale projects of the future. Also important data on the impacts of diversions can be gathered and applied to the future basinwide diversions.

Finally, implementation of small diversions at the local level can help alleviate some of the institutional problems these types of projects traditionally meet. These institutional problems, both short- and long-term, are probably the largest impediment to the implementation of these types of projects. The problems include:

(1) Local funding difficulties - Local government is often unwilling or unable to provide the assurances and maintenance funds for diversion structures. This will be especially true with large diversions where the costs and impacts will be incurred in one area and the primary benefits reaped in another locale.

(2) User conflicts - Freshening of wetland areas will benefit some users and curtail the use of these areas by other users. For example, oyster fishermen are the most seriously affected. Management conflicts can also arise between agencies with different management goals. Conflicts will also arise for water use rights. This will become a greater problem as water uses continue to increase.

(3) Land use changes - Present and future land use in the path of the diversion may be altered. This may cause a conflict with landholders in the area.

(4) General distrust of projected results. There is a traditional distrust of projects of this nature by local residents.

A small diversion which is financially supported by the same people who reap the benefits of the project will aid in establishing the need for such projects in the minds of the locals. Once a smaller diversion has been successful, local people will be more receptive to the larger diversions necessary in the future.

The programs' initial effort in this area was in St. Bernard Parish. The wetlands of St. Bernard Parish have been severely impacted in recent years. Natural deterioration has been greatly augmented by the activities of man. The most significant impact was the dredging of the Mississippi River Gulf Outlet in the early 1960's. Erosion around the area of the canal has increased dramatically due to large wakes created by ship traffic in the canal. In addition, salinities in the area have markedly increased due to intrusion of salt water up the canal (Coastal Environments, Inc. 1977).

As part of a program to attempt the restoration of these deteriorating wetlands, the parish initiated a project to construct a freshwater siphon, designed to deliver between 25 to 500 cubic feet per second over a period from February through March (the period of traditional overbank flooding). The siphon, constructed through the Coastal Energy Impact Program at a cost of 1.7 million dollars, is currently in operation. Presiphon studies were done (Irish 1980) and a postsiphon-monitoring program is currently underway. We hope that data gathered through this project will be useful in modeling other small scale siphons as well as yielding some useful data toward the implementation of the larger siphons.

Probably the most important lesson of this project is the demonstration that the institutional problems at the local level can be overcome when local people are involved with the projects from early in the planning stages.

A priority of the Louisiana coastal research program immediately after implementation, will be a complete planning study of freshwater diversions in Louisiana's coastal zone. This study will refine the water requirements of each hydrologic basin and locate possible diversion sites. Other aspects to be addressed include management goals, water quality impacts, other physical and socioeconomic impacts, and possible alternative funding sources for these projects. We will also continue to work with local govenments to assess the possibilities of small scale diversions.

Coordination of these activities with the appropriate Federal agencies must be maintained to insure that the plans at the State level eventually fit into any larger diversion plans to be implemented in the future.

CONCLUSIONS

A combined local, state and federal effort is the only way that the positive effects of freshwater diversions into Louisiana's estuarine system can become a reality. Local input is necessary to identify management goals and the large institutional problems facing the project. State input is needed to insure coordination between local programs into a basinwide plan and to provide funding for the small scale diversions. For the large scale projects, the State must act as a liaison between the local governments and the Federal agencies. Federal input is necessary to provide planning and construction funds for the large scale diversions.

With this coordinated effort, it is hoped that Louisiana will be able to copy the processes that originally built the State's coastal zone and decrease our annual net land loss.

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REVIEW OF ESTUARINE-RELATED PROJECTS BY THE GULF OF MEXICO FISHERY MANAGEMENT COUNCIL

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ABSTRACT

The Gulf of Mexico Fishery Management Council, a planning group established by an act of Congress, develops management plans for important fish and shellfish. Because these plans consider fishery resources in their entire range of habitat, environmental alterations affecting estuarine-dependents species are viewed with concern by the council. Several public and private projects would significantly alter freshwater inflows affecting gulf fish species. Input and comment by the council on such projects to state and Federal regulatory agencies are effective because (1) the council is a quasi-federal agency whose members are nominated by gulf states governors and selected by the Secretary of Commerce and (2) the council has jurisdiction in water beyond state jurisdiction to 200 miles.

INTRODUCTION

Conservation was a primary factor in the extension of fishery conservation or exclusive economic zones by coastal nations in the mid-1970's. The act of extending jurisdiction was one of management which translates a conservation goal into a tangible and measurable objective. While most of the immediate concerns were expressed over pelagic or bottom-dwelling marine fish species, conservation concerns were logically extended to estuarine-dependent fish stocks as well.

In the United States, the extended jurisdiction legislation is Public Law 94-265, the Fishery Conservation and Management Act of 1976 (FCMA). The Act gives the Federal Government exclusive control over fishery resources beyond state jurisdiction out to 200 miles. FCMA established regional fishery management councils to develop plans for important fish and shellfish stocks in the fishery conservation zone (FCZ). The plans become part of Federal regulations once they are promulgated by the Secretary of Commerce.

The councils are unique creations of Congress. They are neither wholly public nor wholly private. The councils and plans are subject to Federal review procedures yet the councils may enjoin Federal agencies in areas of dispute and interest. Council members are made up of private citizens, state directors of natural resource (fishery) agencies, and several Federal representatives from agencies such as National Marine Fisheries Service, U.S. Fish and Wildlife Service, and the State Department. Private citizens include commercial and sports fishermen, environmentalists, and consumers.

As a region, the Gulf of Mexico has the largest volume and value of fish and shellfish harvests in the United States. It also contains the largest inventory of estuarine areas in the United States. Sykes (1965) and Gunter (1967) have estimated respectively that estuarine-dependent species make up 89 percent of the total gulf catch and 97 percent of the total commercial gulf catch. Management by the Gulf Council of fish and shellfish resources must therefore consider the estuarine habitat and any alterations to it including changes in freshwater inflow.

GULF COUNCIL POLICY

The Gulf Council has enunciated a policy on the estuarine habitat primarily as a result of developing its fishery management plans (FMPs). The Shrimp FMP (Gulf of Mexico Fishery Management Council 1980) in particular documents the importance of estuaries in the life cycle of shrimp. In the early stages of this FMP, the council's Shrimp Advisory Panel, composed of industry members, felt that the issue of estuarine habitat was vital enough to pass a resolution (Appendix 1) for consideration of the council.

The council passed a resolution of its own on January 11, 1978. The resolution (Appendix 2) acknowledges the importance of the estuarine habitat and encourages Federal and state agencies to develop and implement an effective program of estuarine protection and managemnt.

The next enunciation of council policy was that each FMP will, (1) adequately define habitat significant to the fishery to be managed, and (2) include recommendations for changes in habitat, or in habitat policies of responsible agencies, which are necessary to achieve the objectives of the FMP. These requirements were to be the responsibility of the council's Habitat and Environmental Protection Committee. The council directed this committee to review proposed habitat alterations and other human actions which may have significant adverse impacts on fisheries with existing or proposed FMPs. After a review of such projects, the committee will present its recommendations to the council for action, if any.

The Shrimp FMP for a resource extremely dependent on the estuarine habitat, has as one of its objectives, "encourage adequate habitat protection measures." To fulfill this objective a management measure in the FMP (page 8-13) confirms the establishment of the above committee, its responsibilities, and adoption of policies set forth in the National Plan for Marine Fisheries and the Eastland Fisheries Survey (Atlantic States Marine Fisheries Commission et al. 1977) regarding habitat protection and pollution control.

The Habitat and Environmental Protection Committee has developed criteria for reviewing habitat-sensitive projects. The criteria is developed along a size threshold, direct and indirect adverse effects, and specifies:

1. The council would review and possibly comment on projects that directly impact on fisheries for which FMPs are being developed by the council and which directly impact on areas 50 acres or more in total surface area.

2. Projects having a substantial or significant nondirect impact on areas of 50 acres or more such as those causing prevention of surface water flow, reduced detrital export, and saltwater intrusion.

3. A case-by-case review of projects directly impacting less than 50 acres when it has been determined by a field review that it is a precedent-setting project or is a project in a unique or critical habitat area.

METHOD OF COUNCIL INPUT

Having developed a policy on habitat modification and scientific documents (FMPs) supporting that policy, the council is warranted in taking action to protect gulf estuarine areas. The action takes the form of written comment, testimony at public hearings, conducting its own hearings, referral to higher authority, and possible legal action.

Council involvement on estuarine-related projects is directed toward state and Federal regulatory agencies which permit and monitor such projects. These agencies include state resource/environmental agencies, the U.S. Army Corps of Engineers, the Environmental Protection Agency, the Council on Environmental Quality, the National Marine Fisheries Service, and the U.S. Fish and Wildlife Service.

The basis for all council input is its FMPs. Proposed habitat alterations must affect fishery resources, for which there are plans, in order to elicit a council response. Relevant sections of the FMP are cited in communication with the above agencies along with any other scientific literature or ongoing research.

Council participation in review of these projects is both legitimate and effective yet has its limitations. Comment by the council is welcome because Federal regulatory agencies prefer comments from state agencies/officials on projects in that state. Because (1) most council members reflect state concerns, and (2) the council is the sole group with jurisdiction over fishery resources in the FCZ, its comments therefore carry weight and merit. Furthermore, because the council is semi-autonomous from the Federal Government, it could engage in legal actions against the government. (This issue is not fully resolved despite a move in that direction recently by the Mid-Atlantic Council.)

Limitations on council participation in project review are due to its planning nature. The council has no regulatory authority of any kind; FMOs are enforced only through the Secretary of Commerce and U.S. Coast Guard. The council has no research facilities but must rely on its FMPs Scientific and Statistical Committee, and Fishery Advisory Panels. Partly because of these limitations, the council has referred projects to higher authority (those needing a Corp of Engineers permit) or to the Council on Environmental Quality (CEQ).

ESTUARINE-RELATED PROJECTS

The Gulf Council has commented on several projects which would alter the inflow of fresh water to estuaries. In all but one of these projects there were indications that there could be adverse impacts on fisheries resources for which the council had or was developing a FMP. These projects and the extent of council involvement are discussed below.

COLORADO RIVER PROJECT

This project at the mouth of the Colorado River is seven years old and contains two features which impact on fisheries differently. As authorized by Congress, the project has navigation and diversion features which would benefit a broad array of user groups. The navigation features include the construction of two jetties where the river empties into the gulf, a deepened navigation channel and an expanded harbor and turning basin at Matagorda, Texas. The diversion feature would direct most of the flow of the river into East Matagorda Bay as it was before 1927; it includes a diversion dam and a flood discharge channel.

The council became involved with this project in March of 1979 when a public hearing for it was announced. The public notice described a plan without any diversion features. The council objected to this because the navigation features could have decreased fish and shellfish production, while the diversion features would have negated this loss and increased production substantially (U.S. Fish and Wildlife Service 1979).

Initial objections were made with the Corps of Engineers, Galveston, over the separability of project features. The council also appealed to CEQ over this direction in the project. In meetings between the Corps, CEQ and Environmental Protection Agency, an agreement was reached to write an environmental impact statement (EIS) for the diversion features and schedule a timetable for construction of both project features. The council has reviewed the diversion EIS (U.S. Army Corps of Engineers 1980) and has pinpointed three objections: continued separability of diversion and navigation EISs, under-estimates of biological benefits, and under-estimates of economic benefits from the diversion features. These issues have yet to be resolved by all parties.

TEXAS WATER PLAN

In 1968 the Texas Water Plan established tentative allocations of water to supplement freshwater inflow to Texas' bays and estuaries. Texas is a coastal state with valuable fish and shellfish stock which are estuarine-dependent. At the same time, its agriculture, industry, and population places higher demands on water resources every year. The Texas Legislature directed comprehensive studies of "the effects of freshwater inflow upon the bays and estuaries of Texas."

The council became involved because any alteration of freshwater inflow would affect the shrimp resource in particular, and also stocks of groundfish. Both resources have FMPs either implemented or in draft stage. Because the plans may become the basis for future policy decisions on water utilization, coucil review appeared necessary.

Two studies were reviewed: the Nueces and Mission-Aransas Estuaries and the Trinity-San Jacinto Estuary. Council comments focused on the conclusions and methodology of the reports. One particular conclusion was that reduced freshwater inflows would increase shrimp production, a conclusion with which the council disagreed. The council also urged the author (Texas Department of Water Resources) to perform additional verification of the overall model with particular emphasis on extreme instead of average freshwater inflows. Other comments addressed the lack of economic analysis of the alternatives and socio-economic impacts of alternative water uses.

MARCO ISLAND

Florida's west coast is experiencing rapid population growth, from Naples to the Tampa-St. Petersburg area. Even in the face of the 1979-80 recession, business conditions were good for this area and for Florida as a whole. Profitable and appealing residential development has unfortunately decreased Florida's wetlands through dredge and fill operations. A large project, involving over 4,000 acres, is the proposed development of eastern Marco Island.

Council involvement began with public notice of a permit necessary for the dredge and fill operation. Based on destruction of the wetland area and reduced freshwater inflow of up to 30 percent, the council forwarded its objections to the project to the Corps of Engineers. The Shrimp FMP was cited in the comment on a project with non-water dependent uses. Further council involvement has focused on testimony to Florida Department of Environment Regulation which held an administrative hearing over the State permit.

SHRIMP AQUACULTURE

Another project in Florida was a proposed shrimp aquaculture operation which would take place contiguous to a bay in the panhandle area of Florida. The artificial shrimp habitat would be the dredged wetland area next to the bay, with the dredged material providing the building matter for the dikes. Some 300 acres of estuarine area are directly involved.

Although the wetland area is privately owned, alteration of it as above would have had an adverse impact. Freshwater drainage through this estuarine area would not continue, thus affecting detrital export of material for estuarine-dependent species. This probable impact was the basis for the council letter which recommended denial of the permit. The issue was also one of private gain at public expense.

DREDGE MATERIAL DISPOSAL

The problem of dredge material disposal is acute in the Gulf of Mexico because, (1) the long-term effects of the disposal of the material are unknown and (2) 70 percent of all U.S. dredging takes place in the three Corps districts between Galveston and Mobile. The expansion and development of the port of Mobile has produced substantial quantities of dredge spoil, and will do so on an annual basis.

One particular aspect of the disposal problem in Mobile Bay has recently involved the council. A 1974 inter-agency agreement on dredge material disposal identified three areas. Since that time one of the sites proved unfeasible and the second site--the major site of all three--became essentially unavailable for public (Corps) use. The remaining site was an intertidal marsh area providing for a small pass through which the Mobile River would flow into the bay. In all, there are 180 acres involved. The site is still productive despite industrial development and dredged spoil on its boundaries; the area has recently been revegetated after Hurricane Frederick in 1979 destroyed several dikes blocking parts of the area.

The council became involved with this phase of the project since it met the review criteria and was consistent with other issues addressed. There was also an impasse reached between several of the agencies which previously approved the 1974 agreement. The impasse is due to a national policy to preserve wetlands and differing interpretations of the agreement by new personnel because there is only one remaining site.

Input by the council has been directed to the Corps of Engineers recommending denial of the filling permit. After an on-site review of the area and a meeting with the Corps, the council sent a follow-up comment reiterating its position. The council recommended the project applicant seek an alternative site, an existing spoil area as yet undeveloped for industrial use.

SUMMARY

The enactment of the Fishery Conservation and Management Act of 1976 provided for the stewardship of the fishery resources beyond state jurisdiction to 200 miles. In the Gulf of Mexico, most of the fishery resources are estuarine-dependent, and the Gulf Council therefore has taken a keen interest in alterations to this habitat. Council input to projects affecting freshwater inflow to estuaries is proper because of its responsibility and effective because of the diverse interests represented on the council. Input made to date relates to diversion of freshwater; channelization, dredging and spoils disposal; residential development; and private use of a wetland area affecting public resources.

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APPENDIX 1

GULF OF MEXICO FISHERY MANAGEMNET COUNCIL
SHALLOW WATER SHRIMP ADVISORY PANEL

RESOLUTION

WHEREAS, the Shallow Water Shrimp Advisory Panel recognizes the substantial detrimental effects that some developmental or construction activities related to bays, estuaries and coastal waters will have on the nursery grounds and habitat of shrimp; and

WHEREAS, the shrimp fishery is a renewable resource which can continue to produce food and contribute to the economy of the Gulf Region; and

WHEREAS, shrimp are migratory and move between states and cross freely in and out of the fishery management zone;

NOW THEREFORE, BE IT RESOLVED by the Shallow Water Shrimp Advisory Panel that the Gulf of Mexico Fishery Management Council be advised of the panel's concern of the loss of estuarine shrimp habitat; and

BE IT FURTHER RESOLVED that the Secretary of Commerce be requested and urged to utilize any authority she may have under P.L. 94-265, or other Acts or good offices, to protect this resource.

APPENDIX 2

GULF OF MEXICO FISHERY MANAGEMENT COUNCIL

RESOLUTION

WHEREAS, the commerical seafood landings, in the U.S. generate billions of dollars annually for the ecomomy of the Nation; and

WHEREAS, these marine resources also provide food and recreational opportunities for millions of our citizens; and

WHEREAS, habitat alterations, destruction of marsh land, water pollution and many other factors can have a substantial detrimental effect on estuarine nursey grounds and the habitat of estuarine-dependent marine species; and

WHEREAS, our fisheries can continue to be a renewable resource if they are afforded a suitable estuarine habitat;

NOW THEREFORE, be it resolved that we express our concern over the loss and degradation of our estuarine habitat; and

BE IT FURTHER resolved that we urge the governor of each coastal state, their legislative bodies, and their coastal regulatory agencies and officers to utilize any authority they may have to protect and manage this valuable resource for the benefit of all citizens; and

BE IT FURTHER resolved that the Federal agencies with the appropriate jurisdictional responsibility encourage the respectives states to develop and implement an effective program of estuarine protection and management.

Adopted this 11th day of January, 1978 in Biloxi, Mississippi.

John A. Mehos, Chairman

VALUES OF ECOLOGICAL CHARACTERIZATION STUDIES TO ASSESS EFFECTS OF FRESHWATER INFLOW TO ESTUARIES

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ABSTRACT

Ecological characterization studies compile existing information (utilizing a holistic approach) that identifies functional relationships among natural processes and components of coastal ecosystems. Some studies have mapped habitat changes from aerial photographs over a 20-to 25-year time period. The studies integrate environmental and socioeconomic information in a form useful for planning, impact assessment and analysis. Studies completed or underway include the Chenier Plain of Southwestern Louisiana and Southeastern Texas, Sea Islands Region of South Carolina and Georgia, Pacific Northwest, Northern and Central California, Mississippi Deltaic Plain, Texas Barrier Islands Region, Rocky Coast of Maine, Northeastern Gulf of Mexico, and Southwestern Florida.

Data from the Sabine basin of the Chenier Plain study demonstrated the quantified effects of modifying natural river flow on Sabine Lake and the associated estuarine area. Navigation channel developments, construction of reservoirs on the incoming rivers, and impoundment of marshes were the primary causes of ecological changes.

The Mississippi Deltaic Plain study mapped habitat changes from the mid-1950's to 1978. Many of the habitat changes resulted from the modification of freshwater inflow. The study indicated that over 500,000 acres (202,000 ha) of Louisiana coastal wetlands were lost or altered during the period. The information developed from the ecological characterizations will enable planners to understand and predict the consequences of future alterations in the coastal zone.

INTRODUCTION

Estuaries are coastal areas where fresh water mixes with salt water from the ocean. The freshwater needs of estuaries must be balanced with those of humans, industry, and agriculture, if estuaries are to continue to furnish food and recreation at reasonably high levels. Estuaries are our most productive coastal areas, and they require freshwater inflow to maintain their regular ecological processes.

The estimated 27 million acres (10.9 million ha) of estuaries along the U.S. coast have high recreational and commercial fishing value in addition to their use for transportation and industry. They supported an estimated 190 million days of sport fishing in 1975 (U.S. Department of the Interior 1977) and from 60 percent to 80 percent of our commercial finfishes and shellfishes are estuarine dependent; i.e., they require estuaries for breeding or nursery purposes. The commercial catches of the major estuarine-dependent finfishes and shellfishes in 1977 and 1978 had dockside values of 1.7 billion dollars and 1.3 billion dollars, respectively (U.S. Dept. of Commerce 1979).

The areas that have been most adversely affected by changes in freshwater inflow include San Francisco Bay (Smith and Kato 1979), Florida Bay (Snedaker et al. 1977), Chesapeake Bay, the Louisiana coastal marshes, and the Texas gulf coast. The ecological consequences of altering freshwater inflow have been most evident in large estuarine ecosystems such as San Francisco Bay and the Louisiana and Texas estuaries.

Ecological characterization studies include data that can be directly applied to freshwater inflow evaluations. This paper describes how ecological information will be applied to freshwater inflow problems in coastal Louisiana and Texas.

ECOLOGICAL CHARACTERIZATION STUDIES

The U.S. Fish and Wildlife Service's (FWS) Coastal Ecosystem Project within the Biological Services Program initiated a series of studies in 1976 called "coastal ecological characterizations." These studies compile existing available information using a holistic approach that identifies functional relationships among the natural processes and components of coastal ecosystems. An ecological characterization study is designed primarily to integrate environmental and socioeconomic information in a form useful for planning, impact assessment, and analysis, and to identify research needs. A characterization study is a tool that will enable decisionmakers to effectively address coastal problems including planning for urban and industrial developments, determining corridors for pipelines, and siting of onshore and offshore facilities for Outer Continental Shelf (OCS) oil and gas activities.

Between 1976 and 1980 the Coastal Ecosystems Project had nine studies completed or in progress that characterize specific coastal areas of the United States. The Chenier Plain of Southwestern Louisiana and Southeast Texas was completed in 1979. Studies completed in 1980 were the Sea Islands Region of South Carolina and Georgia, the Rocky Coast of Maine, and the Pacific Northwest of Oregon and Washington (Figure 1). The Northern and Central California study is scheduled for completion in 1981, and the Mississippi Deltaic Plain Region and Texas Barrier Islands Region studies in 1982, although various products from these studies are available or will be available in 1981. Studies for the Northeastern Gulf of Mexico (Alabama and panhandle of Florida) and Southwestern Florida and Keys were begun in 1980. Proposed characterization study areas include Chesapeake Bay, Delaware Bay and New Jersey, North Carolina, St. Lawrence Seaway, Southern California, and Beaufort Coast, Lower Cook Inlet, and Bristol Bay in Alaska.

Funds for the nine completed and ongoing studies were provided by

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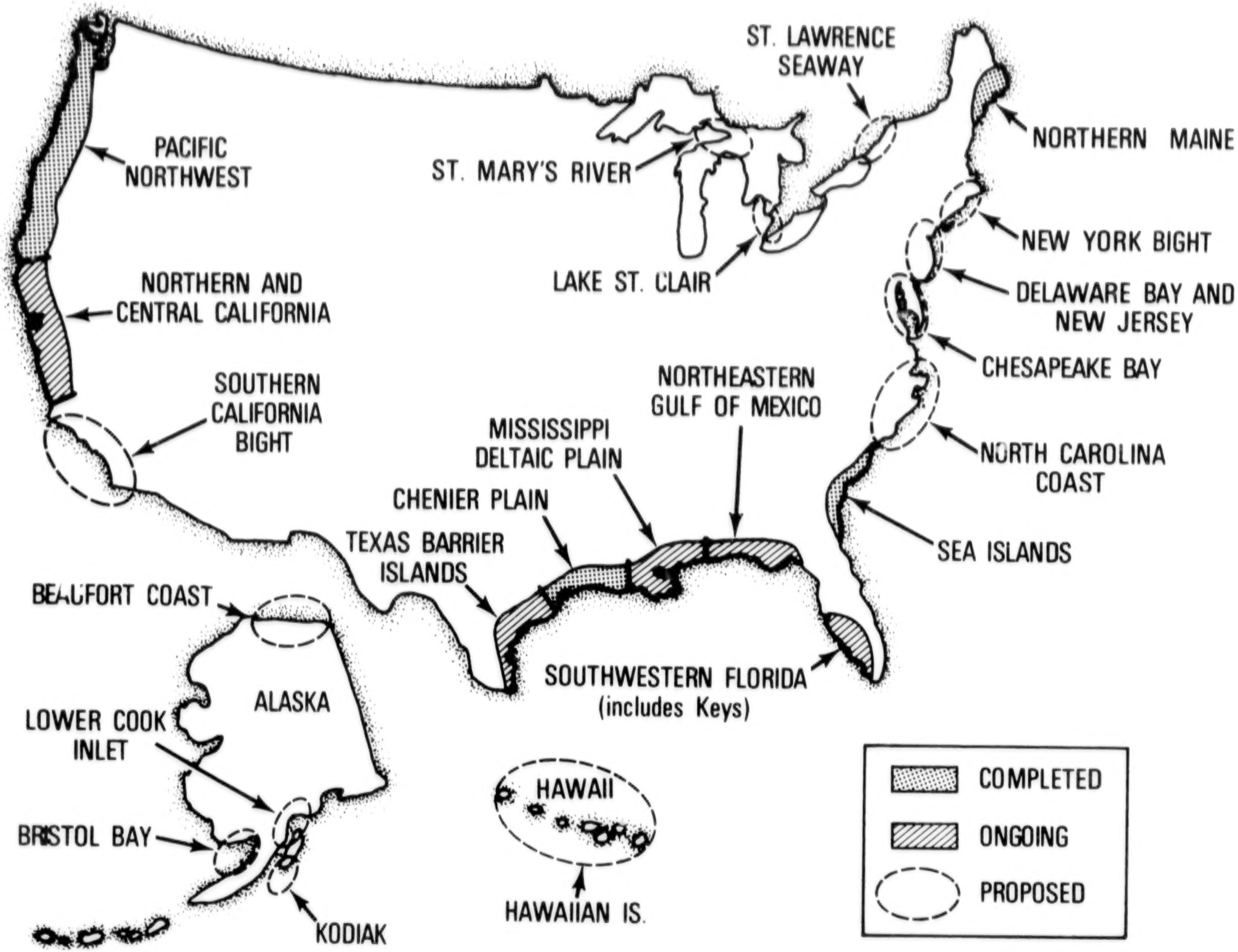

Figure 1. Completed, ongoing and proposed ecological characterization studies for United State Coastal areas.

FWS, the Bureau of Land Management (BLM), and the Environmental Protection Agency (EPA).

CHENIER PLAIN REGION ECOLOGICAL CHARACTERIZATION

The FWS, in cooperation with EPA, conducted an ecological characterization study of the Chenier Plain Coastal Region of Louisiana and Texas (Gosselink et al. 1979). The study was begun in June 1976 and completed in May 1979.

The Chenier Plain coastal region extends from Vermilion Bay, Louisiana to East Bay, Texas. The lengthwise boundaries of the region are the 30-foot depth contour along the shore of the Gulf of Mexico and the 5-foot land elevation contour (Figure 1).

The results of this study are contained in three volumes. Volume I (Narrative Report) briefly describes the characterization process; describes and analyses the climatic, geomorphic, and functional processes that formed or are changing the Chenier Plain; describes the drainage basins and habitats; and gives biological accounts of the more important animal species. Volume II (Appendixes) contains geological, hydrological, meteorological, chemical, biological, and socioeconomic data sources; describes socioeconomic factors, oil and gas production, agricultural values, sport and commercial fisheries, fur trapping, and waterfowl, fishes, and a habitat/species list; and contains data about water discharges, phosphorus levels, and habitat changes.

Volume III (Atlas) consists of ten 1:125,000 scale plates (maps) and one 1:250,000 scale plate with data on the Pleistocene erosional surface, Chenier Plain habitat groups, Chenier Plain wetland habitats, canals and point source discharges, and special features (bird nesting colonies, archaeological sites, refuges and oyster reefs).

MISSISSIPPI DELTAIC PLAIN REGION ECOLOGICAL CHARACTERIZATION

The FWS, in cooperation with BLM, is presently conducting an ecological characterization study of the Mississippi Deltaic Plain Region. The study was begun in July 1978 and will be completed in the spring of 1982. The Mississippi Deltaic Plain Region is defined as that area extending along the coast from the western side of Vermilion Bay in Louisiana to the Mississippi-Alabama state line. The inland boundaries of the ecosystem are those defined by Louisiana Act 361 for the Louisiana Coastal Zone and by the +15-foot land elevation contour in Mississippi. The gulfward extent of the study area is the legal boundary separating state and Federal waters, 3 miles offshore (Figure 1).

The products of the Mississippi Deltaic Plain Region Characterization Study will be habitat maps, an environmental bibliography, socioeconomic maps and report, an ecological atlas, and ecosystems models and narrative. The following is a summary of those products and status:

1. The habitat maps are a collection of 464 mylar overlay maps (scale 1:24,000) depicting approximately 70 habitats of the study area for the mid 1950's period and 1978. Area of each habitat was measured for the two time periods by topographic sheet, state, hydrologic unit, and parish or county, changes in habitats were tabulated (Wicker 1980, Wicker et al. 1980).

2. The environmental bibliography contains over 5,000 references pertinent to the Mississippi Deltaic Plain Region and a user's manual for the computer storage retrieval system. For the convenience of the user, the references are retrievable by author and category, such as geology, hydrology, meteorology, botany, zoology, ecology, and man's influence on plants and animals.

3. The socioeconomic maps consist of a series of 70 maps (scale 1:125,000) depicting features such as oil and gas infrastructure, pipeline routes, transportation features, point-source discharges, recreation, and tourism. Each map is accompanied by tabular data in a map narrative. The report contains a volume of synthesis papers on various socioeconomic activities within the study area, such as oil and gas production, demography, land use, agriculture, commercial fisheries, trapping, recreation, and tourism (Larson et al. 1980).

4. The ecological atlas (to be completed in spring of 1981) will contain 78 maps (scale 1:100,000) and accompanying narratives. Maps will show oystering grounds, fish-spawning areas, sea turtle nesting areas, waterfowl and furbearer concentrations, shoreline changes from 1955 to 1978, boundaries of marsh types, physical properties such as soil types, geologic features, rainfall, and surface salinities; and socioeconomic activities such as conservation and recreation areas, major dredge-spoil disposal areas, point source discharges, and oil and gas infrastructure.

5. The ecosystems models (to be completed in spring of 1982) will consist of detailed "energese" and pictorial models of the ecosystem, as well as a narrative that will compile and analyze all of the data collected in the component parts (listed above) of the study. The models will be accompanied by a user's guide. The narrative supplements the ecosystem models by clarifying the causes and effects of human activities, natural changes, and controlling influences upon the ecosystem and its hydrologic units, habitats, and populations.

TEXAS BARRIER ISLANDS ECOLOGICAL CHARACTERIZATION

The FWS, in cooperation with BLM, is presently conducting an ecological characterization study of the Texas Barrier Islands Region. The study was begun in June 1979 and will be completed in the winter of 1981.

The study area extends from East (Galveston) Bay to the Texas-Mexico border, and from the State-Federal jurisdiction demarcation line offshore to approximately 40 miles inland.

The four products of the study will be an ecological atlas, ecosystems model and narrative, environmental synthesis papers and bibliography, and socioeconomic synthesis papers and data appendix. The following is a summary of those products and status:

1. The ecological atlas (to be completed in the winter of 1981) will contain 606 mylar overlay maps (scale 1:24,000) depicting habitats and selected land uses in two time periods--the mid 1950's and 1979. The atlas will also contain 48 maps (scale 1:100,000) depicting biological and mineral resources, public use areas, oil and gas infrastructure including pipelines, point source discharges and archaeological sites.

2. The ecosystems models and narrative report (to be completed in the winter of 1981) will contain descriptions of the biological systems and their functions within the study area (similar to the Mississippi Deltaic Plain Region Study).

3. The environmental systhesis papers (to be completed in spring of 1981) are ecological overviews on the six estuarine or hypersaline systems (Galveston, Matagorda-Brazos, San Antonio, Copano-Aransas, Corpus Christi, and Laguna Madre) and marine (offshore) system of the study area. The environmental bibliography contains over 1,500 references pertinent to the study area and a user's manual for the computer storage retrieval system. For the convenience of the user, the references are retrievable by author, estuarine, hypersaline, or offshore system, and category (such as geology, hydrology, meteorology, botany, zoology, and ecology).

4. The products of the socioeconmic portion of study are contained in two volumes. Volume 1, (socioeconomic synthesis papers) presents a synthesis of the data collection efforts. Papers were written on oil and gas production, recreation and tourism, commercial fishery, transportation, industrial and residential development, and agriculture. Volume 2 (data appendix) contains data needed to prepare the synthesis papers (Liebow et al. 1980).

CASE STUDIES OF APPLICATIONS OF ECOLOGICAL CHARACTERIZATIONS TO FRESHWATER INFLOW ISSUE

The following case studies were selected to describe how data in ecological characterization studies document the effects of freshwater inflow, and how the studies can be used in freshwater inflow planning.

CHENIER PLAIN REGION (SABINE BASIN)

There has been considerable change in the hydrology of the Sabine Basin and in the rivers that flow into the basin. Gosselink et al. (1979) described the effects of impoundments on the flow of the fresh water to the basin, and the effects of ship channels and marsh impoundments on basin hydrology (Figure 2). The basin straddles the Texas-Louisiana border, and the population concentration and heavy industrial development have modified the basin dramatically. A combination of port development and the construction of reservoirs has significantly modified the hydrologic regime, especially sediment and nutrient transport.

Prior to construction of the Sabine Ship Channel and the Gulf Intracoastal Waterway, the entire flows of the Sabine and Neches rivers were directed through Sabine Lake. Most of the water from both the Neches and Sabine rivers is now diverted into the Sabine Ship Channel. There is saltwater intrusion in the dredged channels, in the ship channel, and in the north end of Sabine Lake. Other interconnecting canals with their associated spoil deposits and ridges have further modified circulation, particularly on the west side of the lake. Total canal length is 1,244 miles covering an area 8,315 acres of 1.4 percent of the basin's total land area.

In addition to the increasing amounts of water being diverted from the Sabine and Neches rivers, two

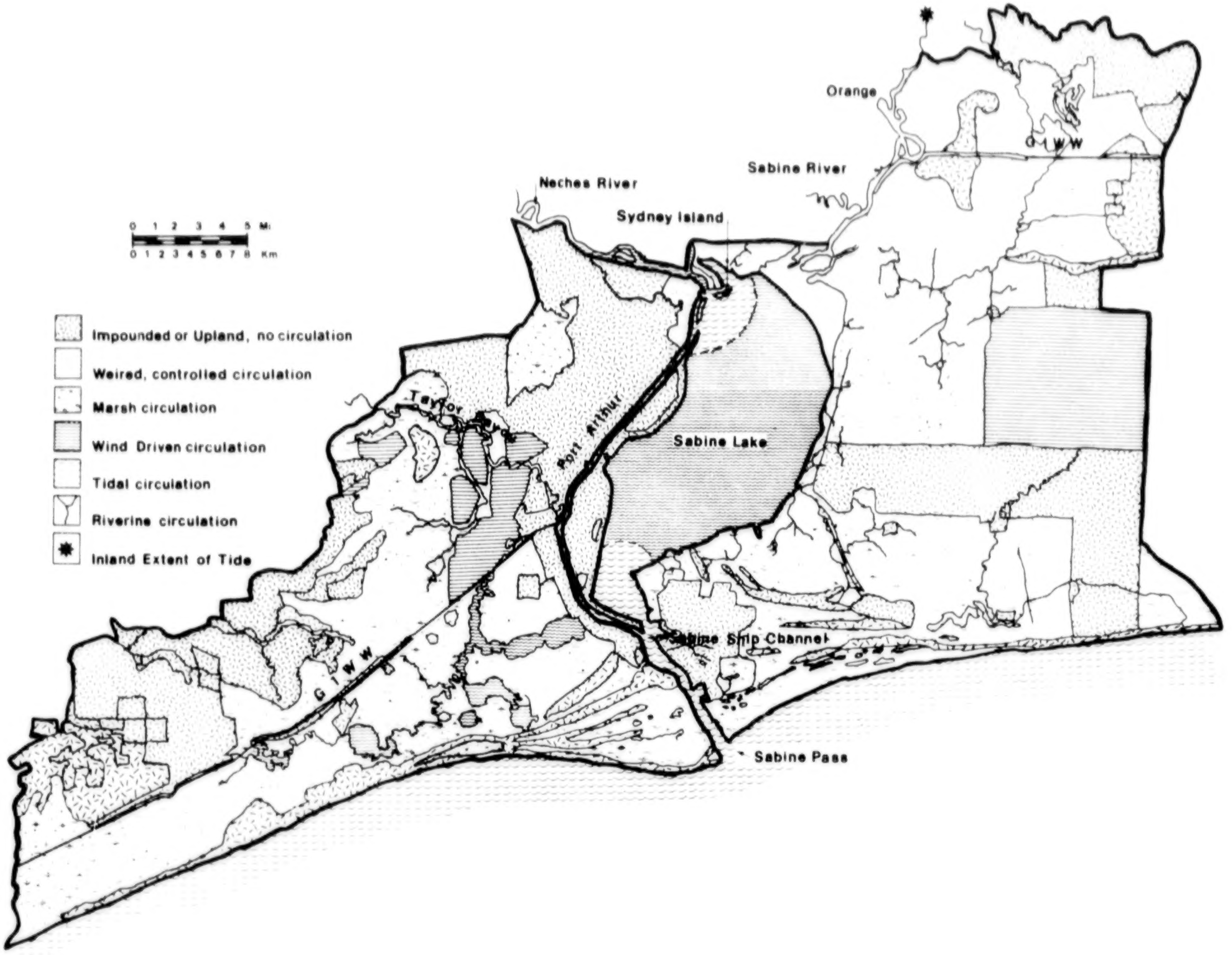

Figure 2. Sabine basin on Texas and Louisiana border showing circulation of water following extensive modification for navigation development, reservoir construction and marsh impoundment. (from Gosselink et al. 1979).

large reservoirs upstream have changed the salinity, modified the timing of freshwater inflow and reduced the amount of suspended sediment normally introduced by the rivers. River discharge has been dramatically curtailed during the spring of the year, when many ecological communities require an influx of freshwater, sediment and nutrients. Nearly 17 percent of the Sabine Basin wetlands (50,736 acres) have been lost since 1952. Direct habitat alterations associated with modification of freshwater inflow include:

(1) enlargement and realignment of ship channels;

(2) construction of dredge spoil areas in Sabine Lake;

(3) construction of 3,937 ft of levees; and

(4) impoundment of 24,711 acres of marshes in Louisiana that had prior connections with Sabine Lake.

Prior to the preparation of the Chenier Plain Ecological Characterization, the total effects of modifying freshwater inflows in the Sabine Basin were not identified because the information was widely dispersed in both published and unpublished reports.

MISSISSIPPI DELTAIC PLAIN AND TEXAS BARRIER ISLANDS REGIONS

The Mississippi Deltaic Plain Region and Texas Barrier Island Region Ecological Characterization study products (in particular the narrative report and ecological atlas with habitat maps) will provide scientists, project planners and managers, regional and national resource planners, local, state and Federal officials, and private entities with much valuable information useful in making decisions on water resource projects and estuarine inflows to Texas and southeastern Louisiana bays and estuaries, and in forecasting the effects of future land use changes.

The ecological atlas will present information on the location, extent and types of wetland existing in the study area in the mid-1950's and in the late 1970's. Wetland delineations will follow the Classification of Wetlands and Deep-Water Habitats of the United States (Cowardin et al. 1977). Selected land use and land cover types in the uplands will be delineated as they existed in the late 1970's. These land use/land cover types will include: urban land; oil and gas facilities; agricultural land (rice fields will be delineated separately); forest land; barren land; barren spoil deposits; and barren dunes. Wetland habitats will include many areas of importance in the study of freshwater inflows, such as riparian marshes and woodlands, impoundments and river deltas. The habitats and land use types depicted in the atlas and described in the narrative report are intimately associated with the three most important aspects of freshwater inflow problems in the estuaries, these being quantity, quality and timing. Structural features which affect the quantity and timing of inflow (such as impoundments and drainage facilities) will be inventoried, as will many features which affect water quality (such as riparian wetlands, marshes and point source discharges). The locations of urban and agricultural lands may be used in investigations of the sources and relative magnitude of toxic substances entering the watersheds.

For example, habitat maps and associated data in the Mississippi Deltaic Plain Region Study indicate that over 500,000 acres (or 800 square miles) of southeastern Louisiana coastal wetlands were lost or altered during the period from the mid-1950's to 1978 (Wicker et al. 1980). This represents an approximate rate of loss of about 25,000 acres (or 39 square miles) per year. The majority of the wetland changes were from marsh to open water. A summary of selected data showed a loss of approximately 487,000 acres of fresh marsh; 88,000 acres of swamp; 63,000 acres of lakes; and a gain of 23,000 acres of non-fresh marsh, 450,000 acres of estuarine open water bodies, 59,000 acres of developed land, and 47,000 acres of spoil areas (Wicker et al. 1980).

By comparing the information from the mid-1950's with that from the late 1970's, trends in factors pertaining to the problem of freshwater inflows may be determined, and the cumulative effects of further alterations within the coastal watersheds may be estimated. Planners and managers will be able to address more effectively the effects of further proliferation of land use features which directly influence freshwater impacts to the estuaries. This capability will be facilitated and enhanced by the narrative report, which will include ecosystem models and detailed discussions of the function, structure and controlling influences of the coastal habitats. The effects of land use changes upon the coastal ecosystems will be explained and (where possible) quantified, enabling the user to understand and predict the consequences of future alterations.

CONCLUSIONS

As evidenced by the examples cited above, ecological characterization studies compiled diverse kinds of information from widely scattered sources. The information is the best available, its sources are verified, and readers are directed to a wide range of referenced source material. The products are accessible to both scientific and technical levels in planning of freshwater inflows to estuaries.

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CHAPTER 11

REHABILITATION OF ESTUARIES THROUGH REINTRODUCTION OF FRESHWATER INFLOW

THE MOUTH OF THE COLORADO RIVER PROJECT

AN ECONOMIC DEVELOPMENT-ENVIRONMENTAL ENHANCEMENT PROJECT

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ABSTRACT

The Mouth of the Colorado River Project will provide a jettied entrance channel in the Gulf of Mexico at the mouth of the Colorado River, Texas; a navigation channel to Matagorda; a diversion channel and dam to divert the flow of the river into Matagorda Bay; and related improvements. A history of project planning is presented to illustrate both interagency conflicts over data needs and proper reporting procedures and interagency cooperation on the studies finally conducted. The studies, which include an economic evaluation of the benefits of river diversion and a delta growth projection based on an in situ sediment study, mathematical modeling, a bay-bottom coring program, and a hydrographic survey are described, and the results of the study are presented. Because the studies show that a river delta of valuable intertidal marsh habitat would form and that additional freshwater inflow would significantly enhance the fishery, construction of the river diversion project is recommended. The project described illustrates the conflicting needs involved in freshwater inflow decisions and the complex data requirements of the decision process, and emphasizes that, because definitive scientific answers to inflow issues are often unavailable, a cooperative attitude among the affected parties is essential if results are to be achieved.

The project area includes the lower 7 miles of the Colorado River and extends from the Gulf Intracoastal Waterway (GIWW) near the town of Matagorda to the Gulf of Mexico. In this reach the Colorado River has a bank-to-bank width of about 300 feet and, prior to the dredging operations of the Colorado River Flood Discharge Channel, a project constructed by the Corps of Engineers in 1973, the river channel depths varied from about 1 foot at the mouth to about 20 feet at the junction with the GIWW. The channel was dredged to a depth of 12 feet and width of 125 feet in 1973. In the half-mile reach immediately downstream from the GIWW, dredged material disposal areas having elevations higher than 10 feet mean sea level are adjacent to the river channel. Downstream from the disposal areas the west bank is about 5 feet high, but it decreases to about 2 feet near the mouth. Sand dunes along the barrier beaches near the mouth of the river are 8 to 10 feet high. Land surfaces of the river banks slope away from the river toward Matagorda and East Matagorda bays. The wide delta of the Colorado River, from the mainland to Matagorda Peninsula, was formed by river sediments over the last 50 to 60 years and is mostly low marsh land except in the area adjacent to the river.

Navigation features of the Mouth of the Colorado River Project include jetties, entrance and navigation channels, recreation facilities, a low-sill weir in Tiger Island Channel, and a harbor and turning basin. The navigation channel, when constructed, will coincide with the existing alignment of the Colorado River. Diversion features of the project provide for full, uncontrolled diversion of the Colorado River into Matagorda Bay. Specifically, the diversion features include a diversion channel from the GIWW to the open waters of Matagorda Bay, a diversion dam in the river, a relocated navigation channel, a dam in Tiger Island Channel, and new oyster reefs in Matagorda Bay.

INTRODUCTION

The Mouth of the Colorado River Project is a shallow-draft navigation project. It was formulated in the early 1960's by the Corps of Engineers to satisfy the need for a dependable navigation channel in the Colorado River between the Gulf Intracoastal Waterway (GIWW) and the Gulf of Mexico. The project was authorized by the Congress as a tributary channel to the GIWW. It is this authorization which provides a basis for the Corps of Engineers' departure from the traditional navigation-only mission to involvement in a project specifically designed to enhance the environment of Matagorda Bay.

The Mouth of the Colorado River Project is located in Matagorda County and on the Texas coast at a point about midway between Galveston and Corpus Christi. The location of the project is shown in Figure 1.

This paper discusses the concerns which surfaced during project planning, describes briefly the studies undertaken to address those concerns, and presents the results and outcome of those efforts. It identifies the interagency differences and cooperation which were a significant part of developing the diversion features of the Mouth of the Colorado River Project. It will also serve to illustrate the technical problems and conflicts which can be expected in any freshwater diversion study and the cooperation needed to arrive at appropriate solutions.

THE AUTHORIZED PROJECT

The Mouth of the Colorado River Project is described in Senate Document No. 102, 90th Congress, Second Session and was authorized by Section 101 of the River and Harbor Act of 1968. As authorized, the project consists of a jettied entrance channel, 15 feet deep by 200 feet wide, in the Gulf of Mexico; a navigation channel, 12 feet deep by 100 feet wide, from the Gulf shore to the GIWW; harbor and turning basin, 12 feet deep by 350 feet wide by 1,450 feet long, adjacent to the north side of the GIWW at Matagorda; a diversion channel, 250 feet wide and varying in depth from 20 to 23 feet, to divert the Colorado River flows into Matagorda Bay; a diversion dam across the existing discharge channel near the junction of the Colorado River and GIWW; bank protection along the Tiger Island Channel; and a public use area with recreational

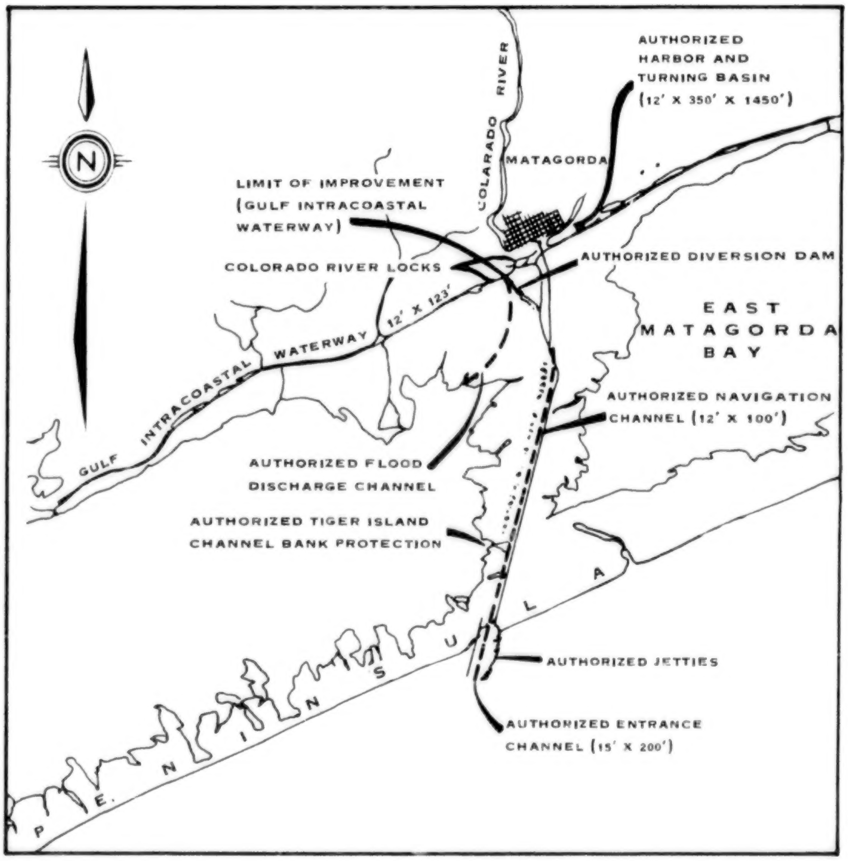
AUTHORIZED HARBOR AND TURNING BASIN (12' X 350' X 1450')
COLORADO RIVER
MATAGORDA
LIMIT OF IMPROVEMENT (GULF INTRACOASTAL WATERWAY)
AUTHORIZED DIVERSION DAM
COLORADO RIVER LOCKS
EAST MATAGORDA BAY
12' X 123'
GULF INTRACOASTAL WATERWAY
AUTHORIZED NAVIGATION CHANNEL (12' X 100')
AUTHORIZED FLOOD DISCHARGE CHANNEL
AUTHORIZED TIGER ISLAND CHANNEL BANK PROTECTION
AUTHORIZED JETTIES
AUTHORIZED ENTRANCE CHANNEL (15' X 200')
PENINSULA
N

Figure 1. Location map.

facilities on land adjacent to the navigation channel. The configuration and features of the authorized project are shown in Figure 2.

BACKGROUND

The primary purpose of the project was navigation. Diversion of the Colorado River was adopted as a means of minimizing the maintenance cost associated with sediment deposition and shoaling in the navigation channel. In effect, the bay was to serve as a natural disposal area for maintenance material from the navigation channel. Although the diversion channel was expected to produce major benefits for the commercial seafood industry as well as small reductions in flood damages in the lower reaches of the river, this feature of the project was incidental to the navigation purpose. In 1968 the projected increases in fishery resources were based on an evaluation of the nutrients and fresh water which would be introduced into Matagorda Bay by the diversion. The evaluation also included an assumption that Columbus Bend Reservoir, a 235,000-acre-foot water supply project under study by the Bureau of Reclamation, would be constructed at river mile 144 near Columbus, Texas. The Columbus Bend Project was expected to reduce the 1,650-acre-foot annual sediment load in the downstream reaches of the river to acceptable levels so that the volume of sediment delivered to Matagorda Bay through the diversion would not fill a large portion of the bay. After the preauthorization studies were completed and the Mouth of the Colorado River Project was authorized, the plans for the Columbus Bend Reservoir project became indefinite. The Water and Power Resources Service (formerly the Bureau of Reclamation) is currently evaluating the feasibility of the Columbus Bend project, as well as other reservoir projects on the Colorado River, but these studies have not been completed.

AGENCY DIFFERENCES DEVELOP

The uncertainties associated with Columbus Bend and other reservoirs on the Colorado River dictated a new basic assumption for the post authorization planning of the project, i.e., existing sediment loads during moderate and high river flows would continue in the absence of the planned reservoirs. The nature and extent of sediment deposition in Matagorda Bay and changes in bay water salinity and circulation patterns, resulting from diversion of the river, would have to be projected, and the effects on the productivity of the bay would have to be evaluated. The total effects of river diversion and sedimentation in Matagorda Bay, although summarily dismissed in the preauthorization studies, were the subject of close and continued coordination with the Fish and Wildlife Service, Texas Parks and Wildlife Department, National Marine Fisheries Service, as well as other concerned agencies from the time post authorization studies were initiated. The Fish and Wildlife Service initially attributed considerable fishery benefits to the diversion feature of the project; but, subsequent reconsideration of the diversion without the upstream reservoirs caused the Fish and Wildlife Service to request substantial additional information. Data on the dispersal of sediments, rate of expected delta development, the distribution of fresh water in the bay, the effects on salinity regime in the bay, and the volume of fresh

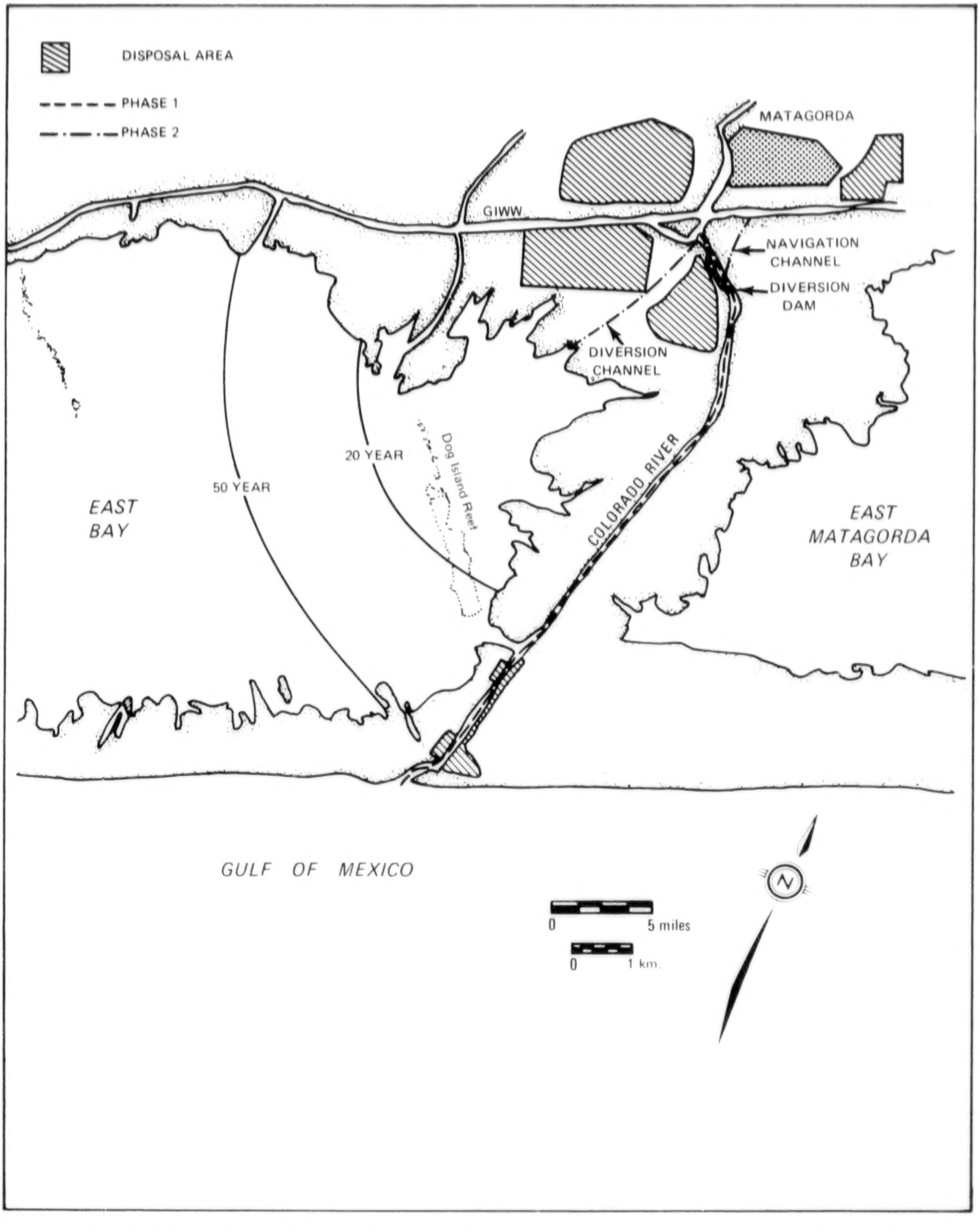

Figure 2. Authorized project.

water that could be expected to be lost to the gulf via Tiger Island Channel were requested. In the absence of accurate data on these aspects, the environmental effects of diverting the river into the bay could not be identified and quantified sufficiently to satisfy the requirements of the National Environmental Policy Act. Consequently, because of the potential hazards associated with large quantities of uncontrolled sediments, the Corps of Engineers took the conservative approach to implementing the authorized navigation project. The project was reformulated to eliminate the environmental risks by eliminating the diversion features from the project. The reformulated project, consisting of only the navigation and recreation features, would still accomplish the primary purpose for which it was authorized, i.e., improved navigation on the Colorado River.

A Draft General Design Memorandum and a Draft Environmental Impact Statement were prepared for the reformulated plan and circulated for review and comment to the other agencies. In subsequent coordination, over a period of 3 years, the fish and wildlife agencies repeatedly and strongly recommended retaining the diversion feature in the plan. When the final reporting documents were prepared, the diversion feature was included; but, because the engineering work on the navigation features was well advanced, a phased approach to project implementation was recommended. Consequently, a staged-construction schedule for the authorized project was developed with the objective of achieving the navigation and recreation benefits of the project while the data collection and evaluation processes for the diversion features were continuing. Construction of the diversion features was scheduled for latter stages. The proposed plan for constructing the navigation and recreational features of the project, as well as the interrelationships between the navigation and diversion features, was presented in a 1977 Phase I General Design Memorandum; the river diversion features of the project were to be addressed in separate Phase I General Design Memorandum and Environmental Impact Statement. Before the studies supporting the diversion reports could begin, more interagency meetings were held, and major agreements between top-level agency executives had to be reached.

Basic issues which divided the agencies concerned the separability of the project features, the degree of certainty that diversion would produce net gains to the bay environment, and the data needed for a sound decision. The fish and wildlife agencies believed that separating the navigation and diversion features of the Mouth of the Colorado River Project would produce unacceptable environmental consequences as well as violate provisions of the National Environmental Policy Act. The Corps of Engineers, on the other hand, was convinced that the two projects, although authorized by the same legislation, were legally, functionally, economically and environmentally separable. The Corps of Engineers advocated immediate construction of the navigation project so that national and local benefits could begin to accrue as soon as possible, but counselled against construction of the diversion project until sufficient information to provide a basis for predicting potential environmental impacts could be developed. The fish and wildlife agencies, convinced of the environmental gains to be achieved by diverting the river to the bay, pressed for concurrent construction of the projects on the basis that sufficient information was already available to make the decisions about the environmental impacts of diversion.

The coordination activities involved an effort to resolve the differences on these issues and were time consuming and costly. To others, particularly the local sponsors and members of the public, these efforts must have appeared pointless and wasteful. Although difficult for some to understand, the lengthy interagency coordination activities, particularly those since 1976, appear to have produced positive results and a clear course of action for implementing both features of the Mouth of the Colorado River Project.

AGREEMENT, COOPERATION AND PROGRESS

In the summer of 1979, while reports on the navigation project were being prepared for submission to the Congress for a construction appropriation, a key interagency meeting was held in Washington, D.C. It was this meeting which produced the agreements necessary to proceed with development of the diversion project on a cooperative basis.

Although the fish and wildlife agencies did not concur in the staged-construction approach, they did agree that additional data on freshwater diversion were needed. The Environmental Protection Agency, however, specifically withheld approval on any dredging activities for the navigation project until the effects of the diversion project were identified. The Corps of Engineers agreed that construction of the navigation features would be delayed until diversion studies were completed and a draft environmental impact statement had been coordinated with the other agencies and the public. This part of the agreement effectively resolved the separability issue because a fully coordinated draft environmental impact statement was expected to eliminate any obstacles to construction of the diversion features. With the filing and approval of the appropriate documents, essentially concurrent construction of the diversion and navigation features of the project would be within reach.

The other major feature of the agreement assigned responsibility for determining the depth of the diversion studies to the Corps of Engineers. The other principal agencies would provide technical input in their respective areas of expertise. With these issues settled, only the studies and preparation of the reports remained to be accomplished.

An intensive study program was developed to accomplish the minimum studies needed to answer the critical questions concerning diversion of the Colorado River into Matagorda Bay. How much fresh water would be put into the bay and how much change in salinity levels would be achieved? How would this change affect biological productivity? How much sediment would be delivered to the bay and where would it be deposited? How much bay bottom would be converted to delta and how much of the delta would become tidal marsh? In addition to these difficult questions concerning environmental changes in the bay, there were the traditional engineering and economic questions asked in all Corps of Engineers' planning studies, i.e., what, if anything, should be done? What is the best alternative? How much will it cost? Who will pay for it? All of these questions were to be answered within severe time constraints.

The cooperative study program consisted of three principal features, a delta growth study, mathematical modeling of the bay, and a benefit analyses. To answer delta growth questions, four basic studies were required, sediment analyses of the river and the bay, hydrodynamic modeling of the bay, a coring program of the bay bottom, and a bathymetric study. The benefit analyses consisted of projecting increased biological productivity and estimates of the economic value of this productivity.

To accomplish the work, the study team included technical experts from the various State and Federal agencies. Also, a private consultant was retained by the Corps of Engineers to produce major inputs for the studies. The Corps of Engineers coordinated the work and supplied the hydraulic and engineering expertise. The U.S. Geological Survey conducted analyses of the river sediment load. The Texas Department of Water Resources provided the mathematical model of Matagorda Bay. The private consultant synthesized the data to produce estimates of the nature and extent of the delta development. The U.S. Fish and Wildlife Service, with the assistance of the National Marine Fisheries Service and the Texas Parks and Wildlife Department, provided technical input on the amount and value of increased productivity to be expected from the diversion. Although, in the beginning, differing opinions and agency responsibilities made it difficult to get the work started, in the end, a wide range of expertise was gathered from both the Government and private sectors to form an effective study team.

STUDIES AND INVESTIGATIONS

The primary goal of the studies was to determine the extent and type of delta building that would occur in Matagorda Bay with river diversion. The results of an in situ sediment study, mathematical modeling of salinity and circulation patterns, core sampling to determine past sedimentation patterns, and a new bathymetric survey of eastern Matagorda Bay were used by the delta growth study contractor, Coastal Environments, Inc., Baton Rouge, Louisiana, to predict delta growth rates. Additional literature and field investigations were made by the Fish and Wildlife Service as a part of its evaluation of the benefits of the diversion features, and an archeological survey was made to locate any cultural resources along the proposed alignment of the diversion channel.

The in situ sediment study was necessary because the only available data on the sediment load of the Colorado River was collected at Columbus, about 135 miles upstream of the project area, and above the Colorado River sedimentation basin at Bay City. Considerable concern existed that the upstream sediment data would not provide valid indication of actual influx of sediment to the project area. Therefore, a field sampling and laboratory analysis effort was designed in consultation with the U.S. Geological Survey and the delta growth study contractor. Field work and laboratory analyses were performed by the U.S. Geological Survey. The analysis and interpretation of results were done by the delta study contractor.

The mathematical modeling effort was executed in two segments. Modeling of circulation patterns, tidal currents, and flood discharge currents were done by the delta study contractor to provide an analytical tool for predicting post diversion sedimentation characteristics. Data from the hydrodynamic model were used as input to the salinity model to predict changes in bay water salinity. The work was done by the Galveston District using models derived from those developed by the Texas Department of Water Resources. Department of Water Resources staff members assisted in adaptation and application of the models. The models consisted of mathematical hydrodynamic and mass transfer models utilizing a one-nautical-mile grid representing Matagorda Bay as a computational base. Initial runs were made to duplicate results of model calibration runs made by the Texas Department of Water Resources to insure that the models were operating correctly, then multiple production runs of existing conditions and with-project conditions were made to predict salinity changes caused by various configurations of river diversion. Additional computer backwater profiles were also developed by the Galveston District to determine design features of the proposed plan and the primary alternative plan.

A field sampling program was undertaken jointly by the Corps of Engineers and the delta study contractor to recover soil cores from the existing Colorado River delta. Projections of future delta growth trends were in part based on historic sedimentation characteristics revealed by the core samples. Cores were taken along transects extending from the existing delta shoreline into Matagorda Bay and analyzed by the contractor in order to evaluate historic prodelta deposition.

A bathymetric survey of the eastern arm of Matagorda Bay was made by the Corps of Engineers. This survey was necessary for determining the existing volume of the bay which, when compared to the inflow rate for river sediments, would determine the rate of delta progradation.

An evaluation of project effects on fisheries productivity in Matagorda Bay was made by the Fish and Wildlife Service in cooperation with the Texas Parks and Wildlife Department and the National Marine Fisheries Service. The goals of the study were to determine the optimum ratio of open water to marsh areas and to estimate the economic value of increases in productivity expected to occur as a result of the proposed river diversion. Required data were gathered from literature and from field inspections. The method developed by the Fish and Wildlife Service for evaluating productivity changes was adopted by the Corps of Engineers for the determination of project benefits.

An archeological survey of proposed work areas was also undertaken by contract with Coastal Environments, Inc. An earlier reconnaissance survey conducted by Comstock and Galloway of the Texas Archeological Survey, University of Texas at Austin, reported no cultural resources in the project area. They attributed this to the fact that land areas are of very recent origin. However, a concern remained that historic shipwrecks could be located in open water areas or buried under recent delta sediments in areas where channel dredging would occur. Therefore, a magnetometer survey was made to identify any such resources that might be damaged by dredging. The survey area was found to contain no anomalies requiring further study.

Benefits attributable to the river diversion project were derived from enhancing the Gulf of Mexico and Matagorda Bay commercial fisheries. The enhancement stemmed from reductions in bay salinities, establishing a salinity gradient in the bay, increased input of nutrients, and creation of new intertidal marsh areas through delta growth. Monetary benefits of the diversion project were evaluated jointly by the Fish and Wildlife Service and the Corps of Engineers, with assistance and concurrence of the Texas Parks and Wildlife Department and the National Marine Fisheries Service. Evaluation of project benefits was separated into three sectors, i.e., the Matagorda Bay fishery, offshore fishery, and benefits of placing oyster cultch material in the bay. Projections for bay fisheries changes were made using a methodology developed by the Fish and Wildlife Service in cooperation with the Texas Parks and Wildlife Department and the National Marine Fisheries Service and reported to the Corps of Engineers in April 1979. The method is based on the hypothesis that diverting the river into the bay will cause a partial return to fishery conditions which existed when the Colorado River discharged directly into Matagorda Bay at Matagorda, before delta growth and related dredging created the present discharge directly to the Gulf of Mexico.

A survey of Matagorda Bay oyster population made by Dr. H. F. Moore in 1904 was used to define historic fishery conditions with respect to oysters in Matagorda Bay. Because of the great detail and apparent accuracy with which the investigators mapped the reefs and processed hundreds of oyster and bottom samples, Moore's study is considered to be a valid indicator of historic oyster population size. The study was conducted by establishing transects across the bay at 300- to 800-yard intervals depending on oyster reef size and density and taking soundings with a pole at 30-yard intervals on each transect to locate oysters and record depths. Once oysters were located they were mapped, and all oysters were removed from a 5 square-yard area. Oyster samples were then separated into those less than 1 inch, between 1 and 3 inches, and over 3 inches to determine population density. The shape and quality of the oysters, species of other animals and plants, and quantity of dead shell were also noted. If a similar study were conducted today, it could be done with greater ease and more quickly because of advances in electronic positioning and bottom profiling equipment, but it is doubtful the results would be more accurate.

Because of present reduced river flow and isolation of East Matagorda Bay by the existing Colorado River delta, the river diversion project is expected to cause only a partial return to the historic condition described by Moore. Therefore, in projecting probable future oyster population densities from diversion, only reefs in the eastern arm of Matagorda Bay, i.e., west of the present Colorado River delta, were considered, and the populations projected on those reefs were reduced 16 percent from those reported by Moore to reflect the effects of an estimated reduction from historic river flows (USCE 1977). Additional adjustments were made to determine the total oyster population projected to be available for harvest and the percentage of that population that would be harvested each year.

Because oystering was the only significant commercial fishery at the time of Moore's study, no historic data similar to Moore's are available for the other fisheries of Matagorda Bay; therefore, an alternative method of projecting probable shrimp and crab harvests was developed. Commercial fisheries statistics were used by the Fish and Wildlife Service to determine the ratio of commercial shrimp and crab harvests to commercial oyster harvests for Matagorda and San Antonio Bays. Because of differences in physical and biological characteristics, each bay has a different ratio of shrimp and crab harvest to oyster harvest. Future shrimp and crab harvests from Matagorda Bay are determined by assuming that the ratio of shrimp and crab harvest to oyster harvest will be similar to the ratio of the bay having overall physical and biological characteristics most similar to those projected for Matagorda Bay after diversion. With anticipated oyster harvest determined, future shrimp and crab harvests were estimated on the basis of the expected ratio of harvests. San Antonio Bay was selected as the most similar to the future Matagorda Bay after diversion, and harvest ratios of 2.6 pounds of white shrimp, 0.7 pounds of brown shrimp, and 3.2 pounds of crabs for each pound of oysters were calculated.

Increases in offshore shrimp harvests were determined separately, and are based on a correlation between freshwater inflow and estuarine productivity. The National Marine Fisheries Service reported an apparent 1 to 1 correlation between freshwater inflows to an estuary and white shrimp population size in that estuary. The brown shrimp population was reported to vary about one-third as much as freshwater inflow. Increases in offshore shrimp catch were calculated by determining the increase in freshwater inflow to Matagorda Bay as a result of diversion and then determining Matagorda Bay's increased contribution to the offshore shrimp harvest by multiplying the bay's current contribution by appropriate factors for freshwater increases and the correlation between population size and freshwater inflow.

The estimated value of the anticipated increased commercial seafood catch was based on the use of dockside prices paid directly to the fisherman or boat owner. It was determined that the existing shrimp, oyster, and crab fleets currently operating along the gulf coast were adequate to harvest the projected increase in commercial seafood products induced by construction of the diversion project. New capital investment (fixed cost) to build additional boats will not be required; therefore, it was not necessary to adjust benefit values derived from dockside prices. Variable costs of the commercial fishermen were also found to have an insignificant impact on benefit values. Therefore, it was determined that use of dockside prices to estimate benefits of diversion was appropriate for this project. However, it may be inappropriate to use dockside prices for similar studies in other areas.

The recommended plan for the diversion features of the Colorado River Project provides for increasing the size of Mad Island Reef, and creating a new oyster reef off Rattlesnake Point by placement of new shell substrate. Using production estimates developed by the Texas Parks and Wildlife Department and dockside prices, benefits attributable to the oyster cultch were derived. These benefits were adjusted to reflect and account for existing production of the reefs.

STUDY RESULTS

Results of the studies showed that full diversion of the Colorado River into Matagorda Bay will produce beneficial changes in the ecology of the bay and tangible national benefits. The volume and characteristics of river sediments and the bay circulation patterns and velocities are such that the diversion project is expected to produce a 2,000-acre delta in 50 years. Left to natural processes, most of the Colorado River delta is expected to develop into a biologically productive low marsh. Freshwater flows of the river will reduce salinity levels in the eastern arm of Matagorda Bay and establish a relatively stable salinity gradient in the bay. The diversion project will also increase the inflow of nutrients to the bay. As a result, tangible benefits amounting to about $10.2 million annually are projected to be derived from enhancing the bay fishery ($8.1 million) and the offshore fishery ($2.0 million) and from placement of oyster cultch in the bay ($0.1 million). These benefits, when compared with the $11 million cost of diversion at the interest rate applicable to the authorized Mouth of the Colorado River Project (3-1/4 percent), produces a benefit-cost ratio of more than 19. At the interest currently prescribed by the National Water Resources Council for evaluating water resources projects, 7-1/8 percent, the benefit-cost ratio of the project is almost 10.

CONCLUSIONS

After years of coordination and speculation over the merits and hazards associated with diverting the Colorado River into Matagorda Bay, basic studies and analyses produced the information necessary for a decision. By diverting the river, a delta will form and cover some bay bottom; but, mostly productive low marsh will be created. Environmental gains will far exceed the environmental drawbacks. Consequently, the Galveston District of the Corps of Engineers has prepared the appropriate reports recommending construction of the diversion features of the authorized Mouth of the Colorado River Project.

Project features, which were described briefly at the beginning of this paper, include a diversion channel, 20 feet deep and 250 feet wide; an earth-filled diversion dam with a crest elevation of 16 feet, mean low tide; a relocated navigation channel, 12 feet deep and 100 feet wide; a hydraulically constructed dam in Tiger Island Channel, and creation of new oyster reefs in Matagorda Bay. The first cost of the recommended plan is estimated at $10,979,000, including the cost of acquiring disposal areas for the excavated material. After construction, the diversion channel is expected to be self-maintaining and the annual operation and maintenance expense will be limited to the diversion dam and a program to monitor the effects of diversion.

The authorized cost-sharing formula for the Mouth of the Colorado River Project was oriented toward the navigation features with the local sponsor required to bear the cost of lands, easements and rights-of -way, relocation of utilities, and disposal areas. At the time of authorization, the diversion channel was considered to be a navigation feature, designed to reduce shoaling and hazards in the navigation channel. Post authorization planning, however, showed that the navigation project could be built without a river diversion, and that the diversion feature's most significant impact was fishery enhancement. The recently completed report, therefore, recommends that the authorized cost-sharing formula be modified to provide for full Federal funding of the diversion features. This aspect is important because many of the local residents do not view the diversion project as being beneficial to their interests and, consequently are reluctant to invest local funds to construct it.

The fresh water contribution issues, particularly those involving diversion of a water course, will not be settled easily. There are many varied views on the subject which stem primarily from conflicting, but valid, water needs. Difficulties are compounded by special interest groups viewing issues from differing value systems, e.g., local vis a vis national viewpoints and development vis-a-vis preservation viewpoints. The Mouth of the Colorado River Project has demonstrated that many important decisions will have to be made in the absence of definitive scientific data. Probably the most important lesson to be learned from the Mouth of the Colorado experience, however, is that action programs which serve the public interest will only occur in an atmosphere of cooperation.

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EFFECTS OF ALTERATIONS OF FRESHWATER INFLOWS INTO MATAGORDA BAY, TEXAS

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ABSTRACT

Matagorda Bay, Texas is experiencing increasing development on its periphery and in its drainage basin. These developments include freshwater inflow alterations and diversions, among others, and require investigations to ascertain ways to manage them to maintain the productivity of the system. Studies being conducted to develop such information and preliminary results are described.

INTRODUCTION

The Matagorda Bay system is one of the principal embayments on the Texas (and the gulf) coast, second in total surface area only to the Galveston System. The most singular feature of the Matagorda Bay System vis-a-vis the other Texas coastal bays is the relative lack of urban-industrial development around its periphery. This is an anomaly of history, for despite its superior geographical situation, the bay system never developed economically to the extent of other Texas bays. In recent years, however, the Matagorda Bay area and watershed have been subjected to increasing development. Since about 1940, 92 percent of the Colorado River drainage area has been regulated by the Highland Lakes reservoirs, and four additional reservoirs downstream have been proposed. On the Navidad River, Palmetto Bend Dam construction has been completed and impoundment in the reservoir has begun. There is a proposal to dredge and maintain the mouth of the Colorado (which has debouched directly into the gulf since the creation of its delta in the 1930's) as a navigation project, and there is an associated proposal to divert the Colorado flow directly into Matagorda Bay. Increased industrial development in the Port Lavaca-Point Comfort area led to the construction of the Matagorda Ship Channel in 1963, so that the bay is now transected by a deepdraft channel, as are most of the other principal bays on the gulf coast. There are proposals to further enlarge this channel. In addition, the increasing pressure of development in the coastal area raises the possibility of future freshwater diversions from the bay and additional wastewater discharges into the bay.

The Matagorda Bay system is, therefore, becoming subject to management problems equivalent to those in other Texas embayments, namely the resolution of the stresses imposed by municipal and industrial developments in the bay area, especially the use of water upstream in the drainage basins, with the requirements for sustaining the bay's ecosystem. The functioning of the estuarine ecosystem of Matagorda Bay is sensitive to the distributions of waterborne constituents such as salinity, dissolved oxygen, temperature and nutrients, which are influenced directly by the alterations to the bay attending development, especially modifications of the freshwater inflow into the bay system.

OBJECTIVES

Given this need for managing Matagorda Bay and its environs, this study was initiated to identify, compile, and synthesize hydrographic and biological information in order to assess the fish and wildlife resources of the Matagorda Bay area and to delineate the dependency of these resources upon the hydrographic characteristics of the bay. The primary use of this information will be to assess the probable effects of several perturbations, by which are meant modifications to the bay environment capable of producing an effect upon the overall hydrography of the bay and hence upon the fishery or wildlife communities dependent upon bay hydrography. Six potential perturbations were identified to be examined as a part of this investigation, of which two are considered here: (1) freshwater flow reductions due to increased capacity of present reservoirs and construction of new reservoirs or other retention and diversion of water; (2) diversion of Colorado River inflow into Matagorda Bay.

PROJECT STRUCTURE

This project began in October 1978 and is being carried out in five phases over a three-year period. Phase 1, Information Synthesis, had the primary purpose of compiling, analyzing, and presenting pertinent existing data on the hydrographic and ecological system of Matagorda Bay and associated habitats. Also included was a preliminary assessment of the impacts of the various perturbations which the bay might experience in the future. The purpose of Phase 2 was to develop a study plan designed to provide information found to be incomplete or unavailable during the Phase 1 studies, both hydrographic and biological, to be performed as Phase 3. Phase 3 is currently in progress. Phase 4 of the project consists of a reassessment of the impacts of the perturbations on Matagorda Bay given the information compiled in Phase 1 and the new, supplementary data gathered in Phase 3, and formulation of recommendations on the management of Matagorda Bay and its environs. The last phase, Phase 5, has the objective of preparing public information in the form of a brochure and slides. The present paper was developed from Phase 1 of this study; the reader is referred to the final report of that study (Ward et al. 1979) for detailed discussions.

Espey, Huston & Associates, Inc. is the prime contractor with the U.S. Fish and Wildlife Service while The University of Texas at Austin has contracted with Espey, Huston & Associates, Inc. to perform a portion of the work. George Ward and James Wiersema are in charge of the Espey, Huston & Associates, Inc. work while Neal Armstrong and Clark Hubbs lead the University's effort.

HYDROGRAPHY

GEOMORPHOLOGY

Matagorda Bay is a lagoonal estuary, and is typical of the gulf Coast embayments in being a broad, shallow system nearly isolated from the Gulf of Mexico by barrier island-peninsulas (Figure 1). Surface area of the bay is about 1,200 km^2 (including East Matagorda Bay) while the mean depth is something over 3 meters, so that the bay has a large surface area-to-volume ratio, a fact of central importance to its hydrography. Numerous shoals and oyster reefs occur throughout the bay system. There are several large peripheral bights and bays which have sufficient physiographic identity to bear geographical names, most important of which are Tres Palacios Bay, Karankawa Bay, Powderhorn Lake, Oyster Lake, and the Lavaca Bay System (itself containing several tertiary bays). East Matagorda Bay is, for practical purposes, separated from Matagorda Bay proper by the delta of the Colorado River which extends from the mainland near Matagorda Peninsula. There are five principal inlets through which elements of the Matagorda Bay system communicate with the Gulf of Mexico: Pass Cavallo, Matagorda Ship Channel landcut, Greens Bayou, the Colorado River Mouth complex and Brown Cedar Cut.

CIRCULATION

The hydrodynamic regimes in the Matagorda Bay system are a function of several complex and highly interactive processes. The principal hydrodynamic influences are tides, density structure (due primarily to salinity variations), meteorological driving forces (e.g., wind and atmospheric pressure gradients) and freshwater inflows from the Colorado, Lavaca and Navidad rivers. Of secondary importance are such factors as Coriolis acceleration, ship traffic, and diversions and return flows. Such events as extreme floods and hurricanes are relatively rare and of short duration, but have major immediate influences on the hydrodynamic regimes in the bay system. As a general rule, the Matagorda Bay system is meteorologically dominated. This is principally a consequence of the large surface area-to-volume ratio of the bay, in conjunction with the intensity and variability of meteorological forcing and small tidal influence.

The feeding rivers are responsible for the estuarine character of Matagorda Bay. These inflows are of extreme variability, when unregulated, ranging over several orders of magnitude of flow, from drought stage to flood. The direct influence of the rivers on circulation in the bay system is limited to moderate to high flows, when the inflows can result in significant currents. However, their indirect influence is important, even at low flows, in establishing salinity variation across the bay.

The principal freshwater inflows to the Matagorda Bay system are summarized in Table 1, and their

Table 1. Gauged and ungauged annual inflow into Matagorda Bay. Colorado River excluded. All flows in cubic feet per second (cfs).

	Gauged Drainage (Period of Record)			Ungauged Drainage (1960-78)	
	River	Flow at Gauge*	Flow into Bay	Watershed	Flow into Bay
Lavaca	Lavaca	316	338	Venado Creek	36
	Navidad**	559	727	Cox Bay	54
	Garcitas	49	187	Chocolate Bay	51
	Placedo	62	115	Keller Bay	66
				East Sheriff Oil Field	41
	Total	986	1,367	Total	248
Tres Palacios	Tres Palacios	143	230	Oyster Lake-Willow Dam Slough	78
				Turtle Bay	69
				Undelineated	32
				Total	179
Matagorda				West Branch Colorado River	48
				Powderhorn Lake	144
				Karankawa Bay	324
				Houghson Lake	7
				Mad Island	12
				Total	535
East Matagorda	Big Boggy	13	32	Undelineated	527
Combined System (Excluding Colorado River)		1,142	1,629		1,489

* See Table 2-5

** At confluence with Lavaca River

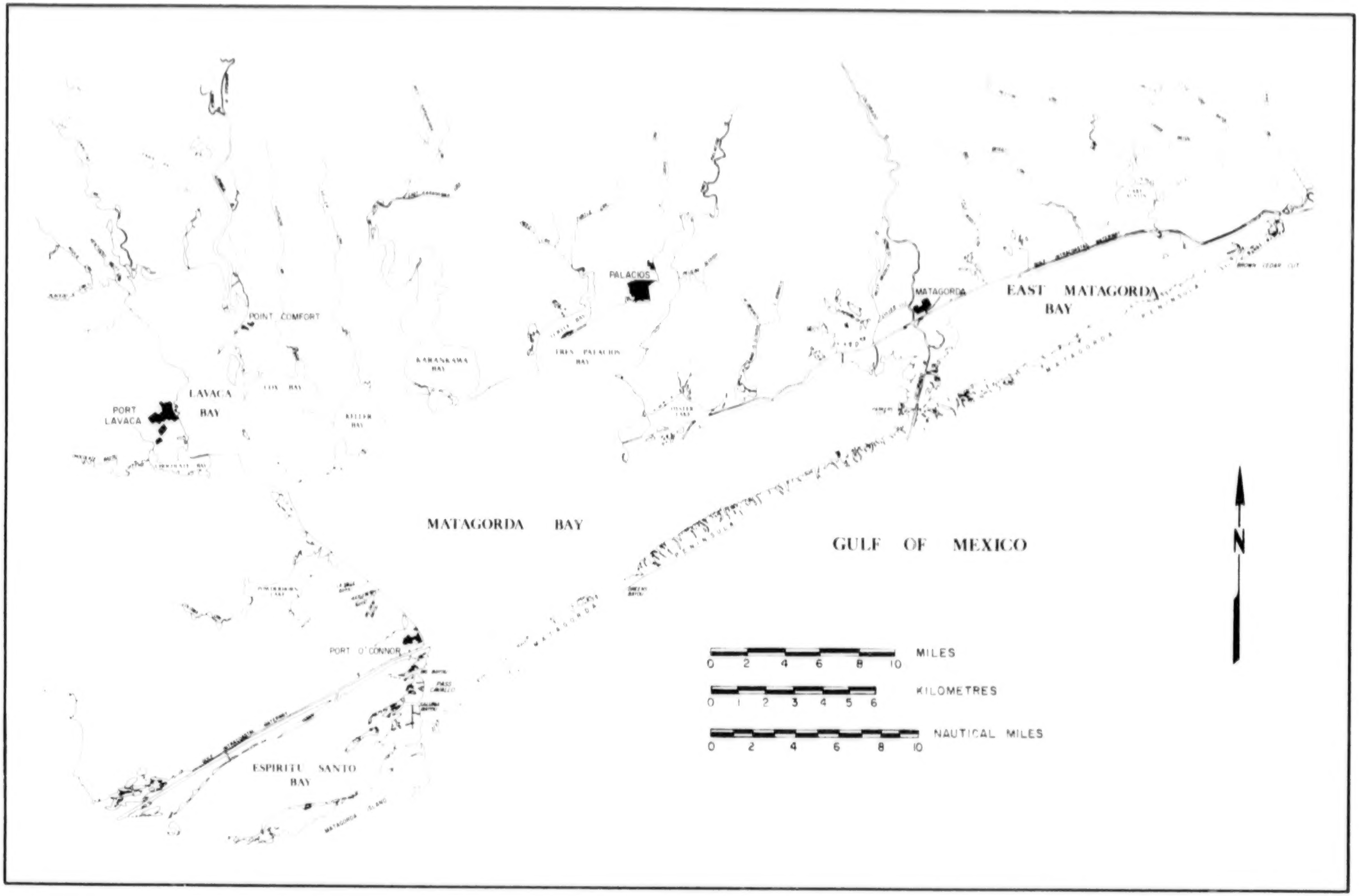

Fig. 1 Matagorda Bay System

relative magnitudes indicated by annual-mean inflow computed from a long period of data (period of record for the inflows with a gauge record). The total annual-mean inflow to the system is about 3,118 cfs (88 m^3/s, 2.26 x 10^6 ac-ft/yr) excluding the Colorado, of which 63 percent is derived from ungauged drainage areas. The annual inflow in the Colorado is an additional 2,430 cfs, (69 m^3/s), of which 0.2 percent is ungauged, but the proportion of this flow that enters the Matagorda Bay system, though probably substantial, is unknown.

The major impoundments of the Colorado River are located in central Texas and comprise a chain of seven man-made reservoirs known as the Highland Lakes, which extend northwest from Austin to 25 miles southeast of San Saba. All of these lakes, except Lake Travis and Lake Buchanan, are managed as constant-level impoundments in which water is retained at fixed storage levels throughout the year. Due to the Highland Lakes system, impoundments further upstream on the Colorado River and its tributaries have minor direct effects upon flows reaching the coastal plain, impounding 25 percent of the drainage area above the Highland Lakes. The proposed Stacy Reservoir will increase this proportion to 32 percent. The effect of the Highland Lakes system on the downstream flow of the Colorado River is small in that there is no systematic alteration in the mean annual flow in the Colorado River due to the Highland Lakes. However, the lakes do have a significant effect upon the sequencing and fluctuations in Colorado River flow.

WATER QUALITY

The quality of water in the Matagorda Bay system is greatly influenced by freshwater inflows, both monitored and unmonitored streamflows, as well as industrial and municipal waste sources (point and non-point). The principal factors which affect the quality of the inflows to the bay system are the physical and hydrologic characteristics of the watershed and the activities of man, such as agricultural uses, oil and gas production, and general municipal activities.

One of the most prominent features of the salinity regime in the bay system is that vertical stratification is generally absent. The broad open segments of the bay are of relatively shallow depths (5 to 15 ft) with large open surface areas exposed to the persistent southeasterly winds of this region of the gulf. As a result, the bay system is generally vertically homogeneous. The only exception is the deep (36 ft) Matagorda Ship Channel which traverses Lavaca and Matagorda bays. Large horizontal salinity gradients frequently exist, from the seawater salinities at the bay system tidal exchange passes, e.g., Pass Cavallo, Brown Cedar Cut and the landcut of the Matagorda Ship Channel, to the near-fresh salinities at river mouths, e.g., Lavaca River and Tres Palacios Creek. As a typical example, the seasonal variation of salinity (and other waterborne constituents) is presented in Figure 2 for lower Matagorda Bay. The normally high inflow period of April, May and June results in minimum salinities during this period, low inflows in July and August result

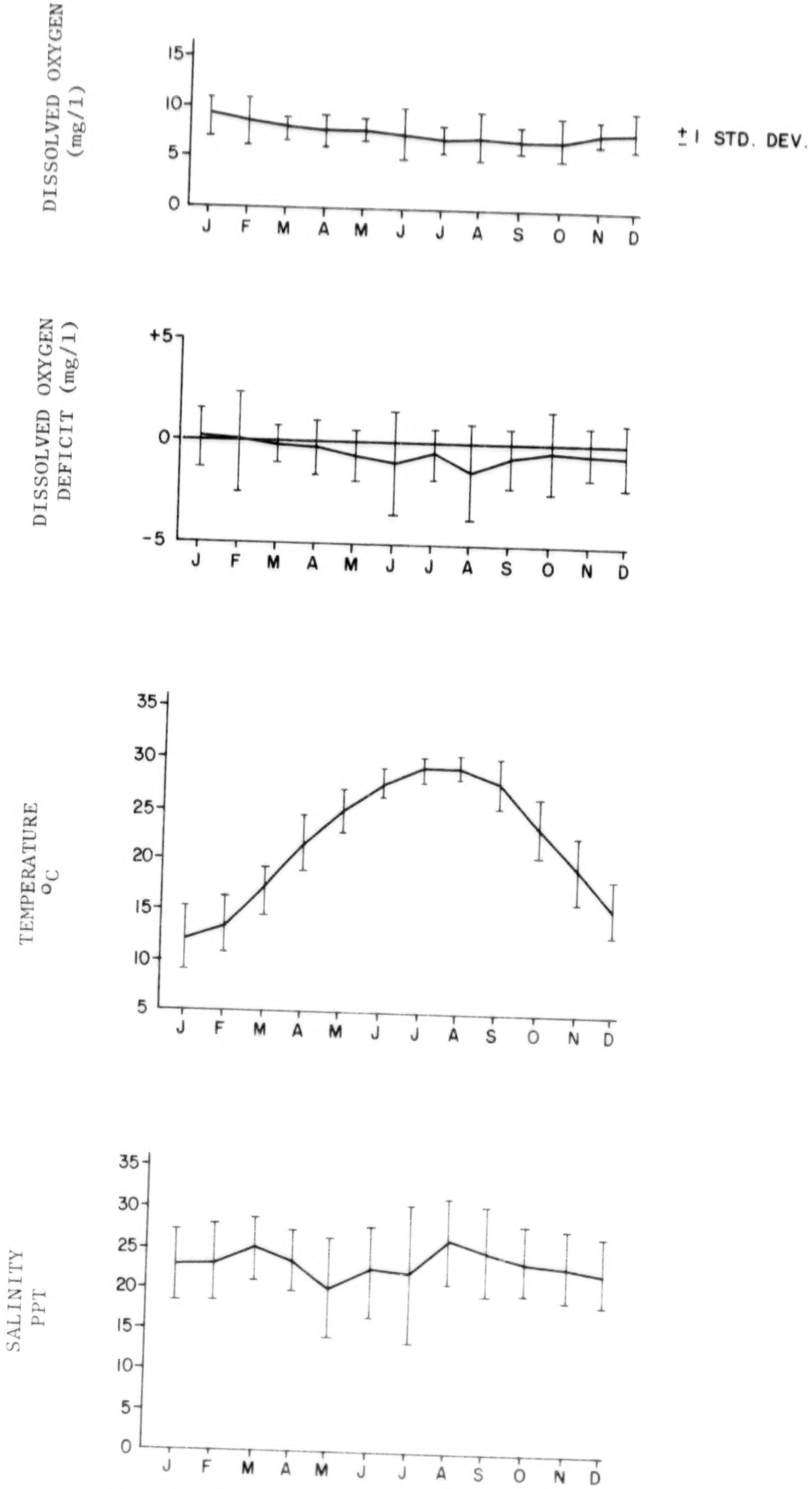

Fig. 2 Seasonal Variation of Waterborne Constituents in Matagorda Bay, Area M-6

in increased salinities, early fall increased inflows again decrease salinities, and the moderate inflows of late fall and winter result in gradual salinity increases to a maximum in March. The salinity variation shown in Figure 2 is typical, though areas more directly impacted by inflows show more pronounced seasonal variations, while areas further removed from the influences of inflows show correspondingly less seasonal variation.

To an even greater degree than salinity, vertical temperature and dissolved oxygen stratification is generally absent in the bay system. The shallow bay depths, strong wind-induced mixing and the small temperature range in the bay system at any one time all tend to result in vertically uniform temperatures, even in the Matagorda Ship Channel. Horizontal temperature gradients are also slight in the bay system and frequently no discernible temperature pattern exists. Though temperatures within the bay system at a specific time are generally uniform, a definite seasonal temperature pattern does exist (Figure 2), as would be expected from climatological considerations. Some slight stratification in dissolved oxygen occurs in the Matagorda Ship Channel, where decreases in dissolved oxygen appear at the greater depths, but even at depths exceeding 30 ft the mean dissolved oxygen concentration still exceeds 5 mg/l.

The available data for nutrients, primarily ammonia, nitrate, total phosphorus, orthophosphates and total organic carbon, are not nearly as extensive as the previous water quality parameters. In general, the available data indicates relatively uniform nutrient levels throughout the system. Nearly two-thirds of the bay's inorganic nitrogen is in the form of nitrate with the remainder in the ammonia form and the nitrite form. Since Matagorda Bay is lightly impacted by the activities of man in comparison to other Texas bays (e.g., Corpus Christi Bay, Galveston Bay and Sabine Lake), numerous nutrient point-source loadings from municipal and industrial discharges do not exist.

PERTURBATION ASSESSMENT

METHODOLOGY

The assessment of a perturbation is effected in two steps. First, the alterations induced by the perturbation upon the physical and chemical environment must be determined. These can include alterations in hydrographic and water quality variables, and introduction of contaminants, and can be interactive. Second, from the alterations in the physicochemical environment, the responses of the biological community must be determined. Both of these steps involve prediction. Methods of prediction can range from judgment, to inference from past behavior (e.g., statistical extrapolation), to the application of sophisticated mathematical models. The responses of the biological system may be approached at three levels of assessment: the individual level, the organism population level, and the community or ecosystem level. In assessing the biological impacts of perturbations in Matagorda Bay, all of these levels of assessment are used as data are available to perform the assessment, and this has been the case for this study.

In order to analyze the Matagorda Bay system and to arrive at operationally useful conclusions within the time frame of the study, an indicator approach was adopted. In this approach, a judicious selection of indicator parameters was made, with the intent that each parameter act as in index to some aspect of the hydrography, water chemistry or ecological community. This is probably the only means by which the historical data on the bay can be analyzed meaningfully. The indicators for the biological system were twenty-five "key species" selected to represent major elements of the bay biological communities. These key species include three seagrasses, seven marsh plants, four shellfish and eleven finfish (Table 2). The indicator hydrographic-chemical parameters were temperature, salinity, dissolved oxygen, depth and nutrients.

ALTERATION OF FRESHWATER INFLOWS

Perturbation Description

All five basins which drain into Matagorda Bay system are expected to experience increased surface water demands in the future as the result of increased agricultural, industrial and municipal activities. Also, additional reservoirs are planned or under consideration which will influence freshwater flows to the system. The Palmetto Bend Stage 1 Reservoir impoundment structure on the Navidad River in the Lavaca Basin is completed. In the Colorado River five potential reservoirs are under consideration (Stacy, Cummins Creek, Clearview, LaGrange, and Columbus Bend). In addition, two cooling reservoirs are under construction which will rely on water from the Colorado Basin. Phase 1 Perturbation Assessment relied upon existing information, viz. published results from the TDWR Reservoir Operations Model (RESOP-II) and Basin System Yield Model (SIMYLN-II), and the analysis of historical data.

From the results of computer simulations of the Navidad River flows for year 2010 water demand (TWDB 1973) with Palmetto Bend Stage 1 Reservoir in operation, mean annual and mean monthly flows were calculated. The ratio of reservoir release (future condition) to reservoir inflow (baseline condition) for an average year varies from 0.487 for August to 0.860 in October, with an annual average of 0.753 or just under a 25 percent reduction in flow the Navidad River, and a net reduction inflow from the Lavaca River system of 16.9 percent.

The results of computer simulations of Colorado River flows are presented in TDWR (1978) for various scenarios including 1980 water demand with all existing reservoirs including the South Texas Reservoir and 2030 water demands for existing reservoirs, the South Texas cooling reservoir, and various configurations of the five potential reservoirs. Baseline conditions were assumed to be represented by the 1980 water-demand scenario and future conditions were assumed represented by the scenario which included all five potential reservoirs with year-2030 water demands. This is a conservative (worst-case) scenario, as all five reservoirs will not be built. Again, mean annual flow and mean monthly flows were calculated from the computer results. The ratio of future flows to baseline flows for the Colorado River varies from 0.28 in August to 0.664 in October, with an annual average of 0.530. Thus, a 47 percent reduction is expected under worst-case conditions.

TABLE 2

STUDY SPECIES

Specific Name	Common Name
PLANTS	
Seagrasses	
Thalassia testudinum	Turtle Grass
Halodule Beadettii (=*wrightii*)	Shoal Grass
Ruppia maritima	Widgeon Grass
Marsh Grasses	
Spartina alterniflora	Smooth Cordgrass
Spartina patens	Saltmeadow Cordgrass
Batis maritima	Saltwort
Salicornia sp.	Glasswort
Monathocloe littoralis	Shoregrass
Distichlis spicata	
Juncus roemerianus	
ANIMALS	
Shellfish	
Penaeus setiferus	White Shrimp
Penaeus aztecus	Brown Shrimp
Callinectes sapidus	Blue Crab
Crassostrea virginica	American Oyster
Fish	
Brevoortia patronus	Gulf Menhaden
Cynoscion nebulosus	Spotted Seatrout
Leiostomus xanthurus	Spot
Micropogon undulatus	Atlantic Croaker
Mugil cephalus	Striped Mullet
Pogonias cromis	Black Drum
Sciaenops ocellata	Red Fish
Paralichthys lethostigma	Southern Flounder
Anchoa mitchilli	Bay Anchovy
Fundulus similis	Longnose Killifish
Cyprinodon variegatus	Sheepshead Minnow

Physicochemical Impacts

Salinity-vs-inflow regressions were used as the baseline flows to obtain the baseline salinity regime in the bay system, and a similar calculation performed with the future flows to obtain projected salinity regimes. In all cases, average salinity changes proved to be small, less than 1 ppt. These predictions of future salinities are long-term averages and do not take into account the fluctuations in salinity associated with transient inflow events. Freshets produce substantial excursions in salinity and their effects last long after the inflows subside due to the long dynamic response of the salinity structure.

The limited data available precluded nutrient-vs-inflow regression studies, so a similar prediction of the effects of reduced inflows upon nutrients cannot be made. A nutrient mass balance was compiled to indicate major sources both in and peripheral to the bay. Freshwater inflows account for about 70 percent of allochthonous carbon sources (62×10^3 kg/d), while phytoplankton dominate autochthonous sources (4.38×10^5 kg/d). Freshwater inflows also account for almost 90 percent of the nitrogen (26.1×10^3 kg/d) and 74 percent of the phosphorus (4.0×10^3 kg/d). It is apparent that freshwater inflows contribute substantial amounts of carbon, nitrogen, and phosphorus to the Matagorda Bay, relative to other external sources. However, at least for carbon, internal production by phytoplankton dominates by two orders of magnitude; in this case an impact due to altered freshwater inflow is dubious. For nitrogen and phosphorus, the reduction of the freshwater inflow source of nutrients would have a substantial impact on the nutrients reaching Matagorda Bay and on carbon production by phytoplankton in the bay given the dependence of phytoplankton growth on nitrogen and phosphorus.

A reduction of freshwater flow does not necessarily imply a reduction of the influx of nutrients into Matagorda Bay; the alterations in concentration must be considered as well as reductions in flow. Some increase in nutrient concentrations can be expected because of increasing waste discharges and reduction of diluting flow due to consumptive water losses; some decrease will result from entrapment in reservoirs; alterations in land-use practices can increase or decrease nutrient concentrations. Quantitative prediction must consider all of these factors.

Biological Impacts

The effects of increased salinity of the above noted magnitudes upon the seagrasses is expected to be minimal because of their wide salinity tolerances and the small expected change in average salinities in the seagrass habitats of the bay. A change in nutrient mass being transported into the bay by reduced freshwater inflows might, over a long period, alter the density of the seagrass populations by altering nutrient concentrations in the overlying water or decreasing the sediment load containing nutrient-rich particles which become part of the substrate. Similarly, little effect is expected for emergent marsh systems due to salinity. However, reduction of productivity may be brought about by freshwater flow reduction because increasing salinity above optimum would reduce growth and fertility of marsh plants. Marsh grasses primarily obtain their nutrients from the sediments (usually of delta origin) in which they grow or through nitrogen fixation, but the role of freshwater inflows in replenishing sediment nutrients is unknown for Matagorda Bay. Another potentially significant influence on marsh plants, which likewise could not be treated in the Phase 1 assessment, is the "smoothing" of freshwater runoff peaks by upstream regulation. This reduces the range of inundation, especially in the delta areas, as well as the seasonal timing of inundation events, and could therefore affect the distribution of marsh plants and associated habitat.

The freshwater inflow reduction will affect the pelagic shellfish environment by modifying water quality (salinity and nutrients primarily) and possibly habitats of certain life stages. A number of studies have dealt with the relation between commercial fishery harvest and freshwater inflows, among these Gunter and Hildebrand (1954), Copeland (1966), Armstrong and Hinson (1973), Chapman (1966) and others. While the exact mechanisms producing this relation are still being debated, salinity levels and nutrient influxes are considered to be the most important variables. The change in average salinities of 2 ppt year round should have little effect upon the white shrimp population of the Matagorda Bay system. Of concern, however, is the extent to which low salinity areas in secondary and tertiary bays will be reduced in size with reduced freshwater inflows and the effects of a reduced nursery area would have on the white shrimp. Since the brown shrimp in general prefer salinities between 20 to 30 ppt, an increase in salinity should directly favor brown shrimp production by allowing the shrimp to utilize more nursery grounds as their habitats.

Shellfish production may be decreased if a decrease in organic and inorganic nutrient influx to the bay actually results from a decrease in flow rate. A reduction in nutrients would have a twofold effect, a reduction in the organic nutrients directly available to the shellfish as well as organics produced through photosynthesis utilizing inorganic nutrients. The effect of a decrease in inorganic nutrient input on shellfish production is not clear because it is not known whether bay productivity is now limited by inorganic nutrient concentrations or some other factor. The concentrations of nitrogen presently in the bay are very close to those concentrations producing maximum phytoplankton growth, and phosphorus concentrations are in excess. An important concern is whether light is already limiting; if so, then a reduction (or increase) of nitrogen may have little impact. A similar situation was encountered in Galveston Bay, as discussed by Armstrong and Hinson (1973). Preliminary calculations of light limitation made from Davis' (ca 1978) data indicated that light may be limiting at times. Organic nutrients are therefore logically the more important impact to consider, but as noted above, the major source of organics in Matagorda Bay is phytoplankton with freshwater inflows and marshes accounting for less than 1.5 percent of the total. If shellfish production is based on organic nutrient sources, then phytoplankton must be considered the major source (but they are influenced by inorganic nutrient influxes, which may result more substantially from freshwater sources). If food sources are not limiting, then salinity may be the major controlling variable affected by freshwater inflows. In summary, though freshwater inflows are indeed important as a salinity control and as a source of nutrients, which function is the more important cannot be determined without further investigation of Matagorda Bay itself.

No long-term impact on *Crassostrea virginica* is anticipated either due to osmotic stress or change in numbers of parasites or predators associated with increases in a change of salinity of less than 2 ppt. Of concern is the moderating effect of freshwater inflow reductions on peak flows, those that reduce salinities low enough to control organisms such as the oyster drill, *Thais haemastoma*, and the parasite *Labyrinthomyxa marina*. An analysis of such peak flows required such as performed by Armstrong and Hinson (1973) for Galveston Bay is needed to appraise this impact.

Like the shellfish, the small increase in salinities produced by the reduction of freshwater inflows should not cause significant changes in the populations of any of the finfish studied. The average salinities expected are well within their tolerance and preference limits; however, local changes in the secondary and tertiary bay margins, bayous, marshes, and so forth are likely to be greater than the changes in average salinities, and the impact of these increased salinities may be substantial. The most serious impact is likely to be the loss of suitable, low salinity, nutrient-rich habitat needed for almost all the finfish larvae and/or juvenile forms. Loss of this important habitat, because of increased salinities which are lethal to the food sources or more likely because of the decrease in nutrient influx with freshwater inflow, could decrease the populations of these finfish over the long term in Matagorda Bay. The adult finfish will be impacted to the extent that their food sources are impacted. Reductions in these food sources due to freshwater inflow reductions would naturally be detrimental to these fish.

COLORADO RIVER DIVERSION

Perturbation Description

The Rivers and Harbors Act of 1968 authorized channel and harbor improvements to the mouth of the Colorado River. Phase 1 consists of the construction of the following improvements: navigation channel, jettied gulf entrance, Parkers Cut stabilization and weir, protected harbor, and recreation facilities. Phase II includes the construction of the following features (Figure 3): flood diversion channel, diversion dam, and realignment of navigation channel. Several alternative plans for diverting Colorado River flood flows were proposed by the Corps of Engineers. One plan calls for complete diversion of all Colorado River flows into Matagorda Bay; however, recent discussions have included the possibility of diverting only those flows less than 3,500 cfs into Matagorda Bay. Flood flows would then continue to be routed down the navigation channel to the Gulf of Mexico. An earthen dam will be constructed across the navigation channel south of the GIWW,

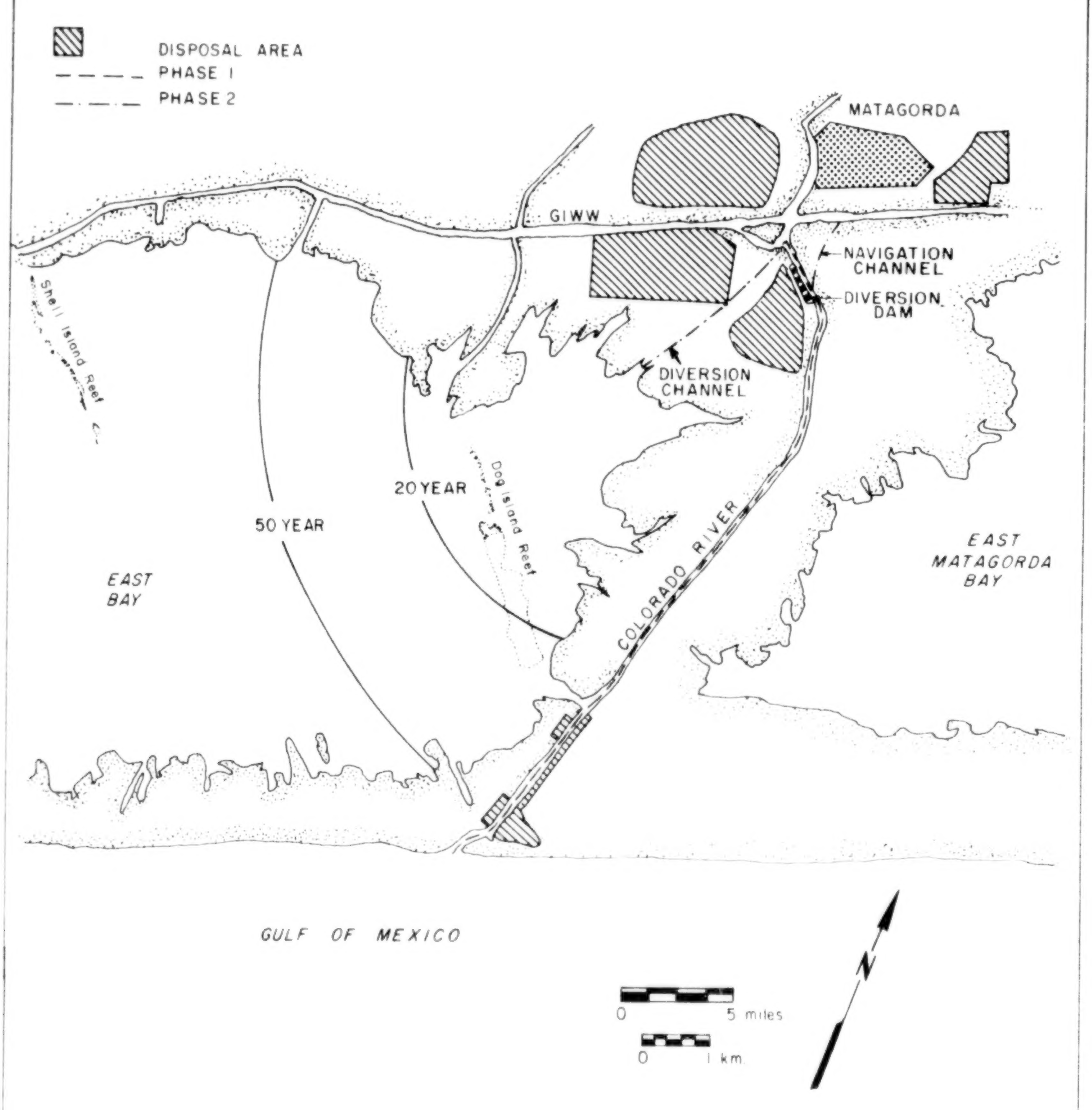

Fig. 3 Mouth of Colorado Project Showing Projected Development of Delta.

diverting Colorado River flows into Matagorda Bay through the flood diversion channel.

Physicochemical Impacts

Navigation improvements to the mouth of the Colorado River, especially the Phase II river diversion and associated freshwater inflow, will have significant hydrological and hydrographic consequences, most important of which are associated with salinity, nutrients, hydraulics, erosion, and sedimentation. Some of these impacts are considered in USFWS (1979). The phase II diversion feature with the proposed dam and channel modifications will modify the hydraulics and circulation patterns in the Matagorda Bay system. Modification in hydrodynamics will affect mixing patterns, salinity structure, nutrient transport, and sedimentary processes. Deposition of sediment in the bay at the outlet of the diversion channel will result in loss of bottom habitat and nursery areas. The deposits may also tend to segregate some shallow areas of the bay, hindering circulation patterns and possibly altering the physical and chemical characteristics of the area.

Predictions of the amount of sedimentation likely to occur with the proposed diversion of the Colorado River have been advanced by the Corps of Engineers (USCE 1977). They predict a maximum 50-year sediment deposition of 13,000 acres, or an average delta growth of 260 acres per year, and a minimum 50-year sediment deposition of 5,700 acres, or 114 acres per year. This estimate is based on full diversion of the Colorado River. If flood flows (8,500 cfs) are routed down the existing navigation channel, much of the sediment which would have been deposited in the bay would be released to the gulf.

The growth of the Colorado River delta was accelerated markedly in 1930 with the breaching of the log jam. The delta then built at a nearly constant rate indicating that the Colorado could not now sustain a delta growth of this magnitude. The preliminary report by van Beek and Gagliano (1979) predicts 36.8 acres/year. However, to provide a conservative estimate, a high rate of 100 acres/year was assumed in the present study, and the resulting sediment area is displayed graphically in Figure 3. More exact predictions of the rate and extent of deltation following the diversion of the Colorado River flows cannot be determined without further studies of sediment loads and grain-size distribution, flow rates, and depositional patterns in the present system.

This diversion of fresh water from the Colorado River can be expected to decrease salinities in the eastern arm and therefore increase the salinity gradient. Further, the nutrient and detrital influx of the Colorado will be diverted into the bay. The bay could still be expected to receive a portion of the flood flows. The navigation improvements will modify flow distribution in the reach below the GIWW and in the Parkers Cut area. The deepened navigation channel, removal of the gulf bar, and installation of jetties will increase the influence of the gulf in the lower reach. Tidal exchange and salinity intrusion will be increased. However, there are no quantitative predictions available of these effects on the Matagorda Bay system.

If the entire flow in the Colorado is diverted, and it is assumed that at present 50 percent of the River discharge enters Matagorda Bay, the project will alter the inflow contribution of the Colorado from about 1,200 to 2,400 cfs annually, i.e., an increase of 25 percent in the total (gauged and ungauged) inflow to the entire bay system. To the planning horizon of 2030, the Colorado flow will decline to 1,300 cfs, so that over the long term, the diversion will practically compensate for upstream use. This, of course, does not account for altered nutrient loads (which are not necessarily proportional to river flow) nor for alterations in time variation of inflows due to the additional watershed development.

Biological Impacts

The major impacts of the Colorado River diversion project will be habitat removal and drainage alteration at project sites and disposal areas, short-term effects of dredging, gain of habitat in disposal areas and in the enlarging river delta, and salinity changes and altered nutrient influx associated with the river diversion. The dredging of the diversion and disposal of spoil will destroy some of the seagrass beds as will the sedimentation of material in the diverted flow. However, new areas suitable for growth of seagrasses should result at the face of the new delta as it progrades into the eastern arm of the Matagorda Bay. While some features of the project will displace emergent marsh habitat directly or indirectly, the new river delta formed by sedimentation of material in the Colorado River would provide new tidal marsh areas suitable for emergent vegetation but the areal extent cannot be reliably estimated at this time.

In general, the diversion of the Colorado River will probably modify shellfish populations in the area, because of altered external nutrient influxes (which may increase with an increase in river-supplied nutrients or decrease because of loss of vegetation due to spoil disposal and channelization and internal influxes from phytoplankton), and replacement of medium salinity nursery grounds by low salinity nursery grounds in the eastern arm of the system. Because young white shrimp prefer low salinities of less than 10 ppt and the organic material brought in with fresh water producing those low salinities, the initial decrease in salinity due to diversion of the Colorado River should favor them.

The freshwater diversion will have mixed effects on oysters, in that while it will increase the flow of fresh water and may increase nutrient influx into Matagorda Bay, it will also increase sedimentation. The results will be, on one hand, lowered salinity and reduced predator and parasite impacts but, on the other hand, increased siltation and turbidity, hence clogging of gill structures of the oysters. The most serious impacts will be due to sedimentation. The predicted rate of delta development is sufficient to eliminate Dog Island Reef in only a few years. Shell Island Reef may also be impacted, depending upon the precise rate of delta growth and the configuration assumed by the enlarging delta.

The finfish studied are euryhaline, and the reduction of salinity in the bay as a whole from the existing salinities would have to change considerably to affect these species. Such a change seems unlikely and, at any rate, will become negligible as the horizon year of 2030 is approached. The turbidity while it may result in avoidance of the area by some of the fish (Fore and Baxter 1972), will be a short-term effect only. If the diversion of the river produces an increase of nutrient influx, it could be beneficial for the finfish by enhancing primary and secondary production. Of major concern is the sedimentation in nursery areas associated with new delta formation, but finfish nursery grounds in this area are expected to advance ahead of the prograding delta while old nursery grounds will be lost.

CONCLUSIONS

The Matagorda Bay Project is a three-year study focusing primarily on the effects of altered freshwater inflows on the living resources of the bay. Two specific types of alterations are being considered, reduction of flow in the two major freshwater sources, the Lavaca River and Colorado River, and the diversion of a portion of the Colorado River flow into the eastern arm of Matagorda Bay. For the former alteration, the major concern is loss of nursery areas in secondary and tertiary bays and possible loss of nutrient inflows. For the latter alteration, the major concern is the loss of shallow bay habitat through sedimentation and the extent to which this loss is offset by the production of new emergent marsh habitat. Both concerns must await completion of the later phases of the project to determine their extent.

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SEDIMENT--ASSET OR LIABILITY

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ABSTRACT

Sediment introduction is a corollary of river-associated freshwater inflow in many estuaries. These sediments represent an asset relative to delta building and associated estuarine wetlands, a liability in maintaining navigation access. A multipurpose approach to resolving this conflict is the separation of navigation from sediment-laden freshwater inflow. Such a separation, as authorized for the Colorado River, provides dual benefits: reduced maintenance dredging and increased fish and wildlife resources. In contrast, failure to do so at the Lower Atchafalaya River, Louisiana, increasingly results in dual cost. Comparison of the two projects raises serious questions about the consistency of project evaluation and cost/benefit analysis.

INTRODUCTION

Estuarine environments that are subject to direct inflow of river water invariably serve as a receiving basin for the sediments carried by these rivers. Depending on the coastal setting, in particular water depths and tidal and wave regimes, and on the discharge and load characteristics of the river, variable amounts of this sediment may be retained and form the basis for development of new wetlands. This process may range from minimal shoreline accretion, to replacement of the entire estuarine water body by wetlands and even to progradation into the marine environment in the form of a delta, as is the case with the Mississippi River. In this latter instance, estuarine environments develop between major distributaries of the delta system.

Thus, sediment is one constituent of freshwater inflow into estuaries that merits major consideration as a factor contributing to the dynamic and ephemeral nature of the estuarine environment. Through its sediment, riverine inflow has the ability to change environments spatially and through time and is doing so in many cases.

It also follows that by modifying riverine inflow into the estuarine environment, the direction and timing of estuarine changes as related to sedimentation are modified. This raises the question whether sediment should be considered an asset or a liability. That question appears in dire need of an answer when comparing two water resources projects affecting introduction of river water and sediment into estuarine systems along the gulf coast. These are the projects associated with the Colorado River in Texas and the Lower Atchafalaya River in Louisiana.

MOUTH OF COLORADO RIVER PROJECT

The "Mouth of Colorado River Project" involves the reintroduction of Colorado River discharges into Matagorda Bay by means of a diversion channel and dam (Figure 1). The project was initially conceived and authorized primarily for navigation purposes (U.S. Army Corps of Engineers [USACE] 1977). The objective was to separate navigation from the Colorado River and thereby negate adverse effects of flood discharge and sedimentation on channel conditions below the crossing of the Colorado River and the Gulf Intracoastal Waterway. Potential environmental benefits to be derived from reintroduction of fresh water into Matagorda Bay were considered incidental to the project. However, when post authorization studies indicated that sufficient navigation and flood control benefits could be achieved without diversion, the diversion feature became a semiseparate project primarily for the purpose of environmental enhancement (USACE 1980). Proposed cost-sharing was revised accordingly with 95 percent to 100 percent of the cost of the diversion apportioned to the Federal Government. The diversion project, with a first cost of $10,000,000, remained viable on the basis of a 20/1 benefit/cost ratio.

Benefits to be derived from diversion of the Colorado River flow into Matagorda Bay relate directly to partial restoration of historic conditions of freshwater inflow and delta building as occurred from the turn of the century until 1936 when the Colorado River Channel was extended through Matagorda Peninsula into the Gulf of Mexico. These conditions are summarized in Figure 2. Delta building initially was subaqueous and apparent from the need for channel dredging into Matagorda Bay as early as 1921. Thus, most likely, a subaqueous platform of fine-grained sediments (a prodelta) set the stage for the rapid subaerial development which came with the flood years of 1935 to 1938 and clearing of rafts from the lower Colorado River Channel. Within the context of this paper it is important to note the effect of channelization on Colorado River delta growth. Initial delta development followed the typical pattern of progradation along a broad front by means of multiple distributaries as is common in shallow-water environments with limited tidal and wave action. Most notable was the subdelta lobe associated with the Egret Island distributary. However, subsequent to this initial development, attempts were made to maintain an unobstructed channel into Matagorda Bay through dredging ahead of the advancing delta. The extended channel and associated spoil deposits limited further distributary development and induced a linear growth pattern across Matagorda Bay. With the extension of the channel across Matagorda Peninsula in 1936, additional maintenance dredging and spoil disposal, and the construction of reservoirs along the Colorado River, delta development practically terminated. The only exception is the limited growth occurring at the diversion provided by Tiger Island Cut since the 1950's.

In considering the benefits to be derived from the proposed diversion of all Colorado River flows,

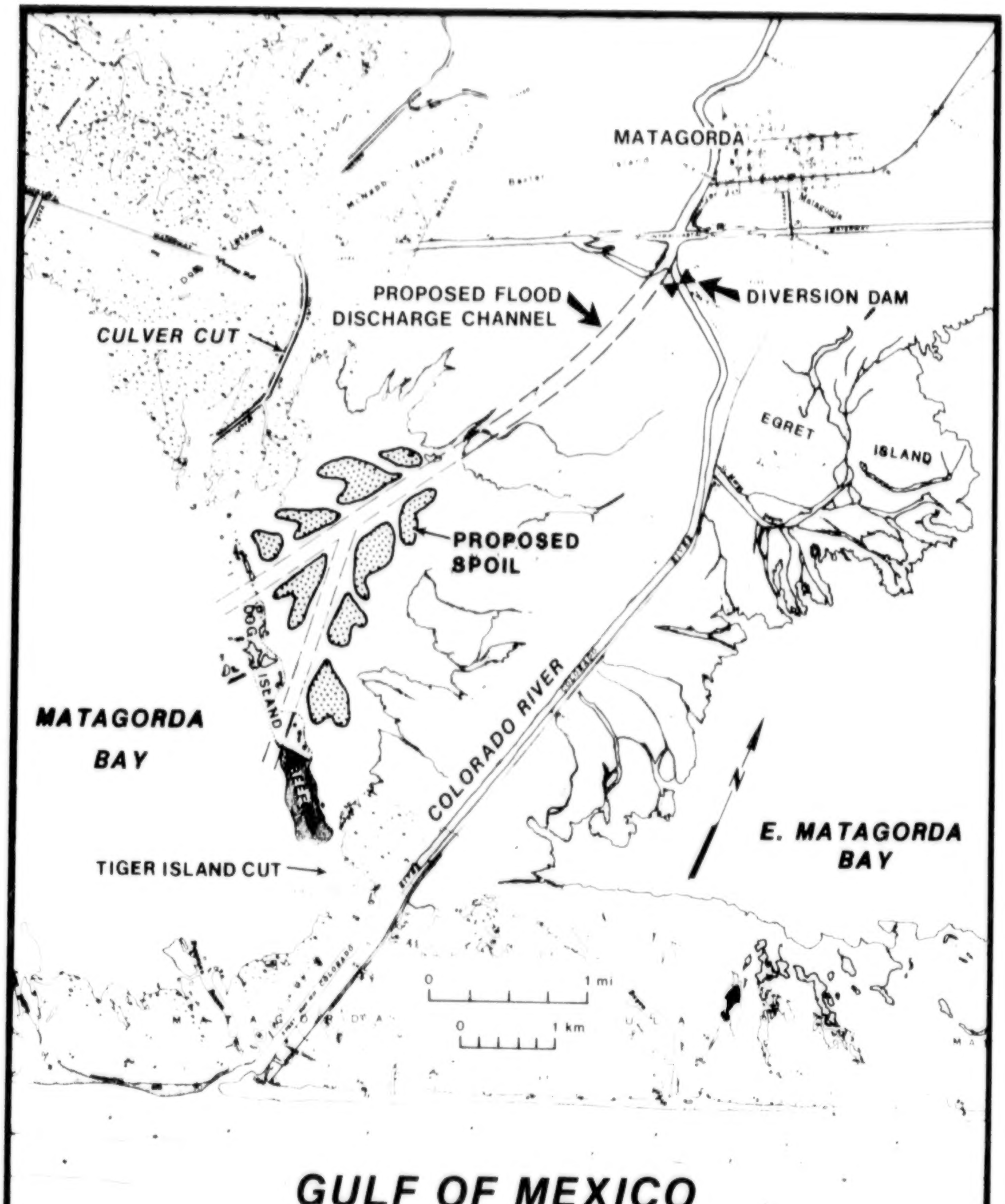


Figure 1. Design for diversion of Colorado River flows into Matagorda Bay, Texas.

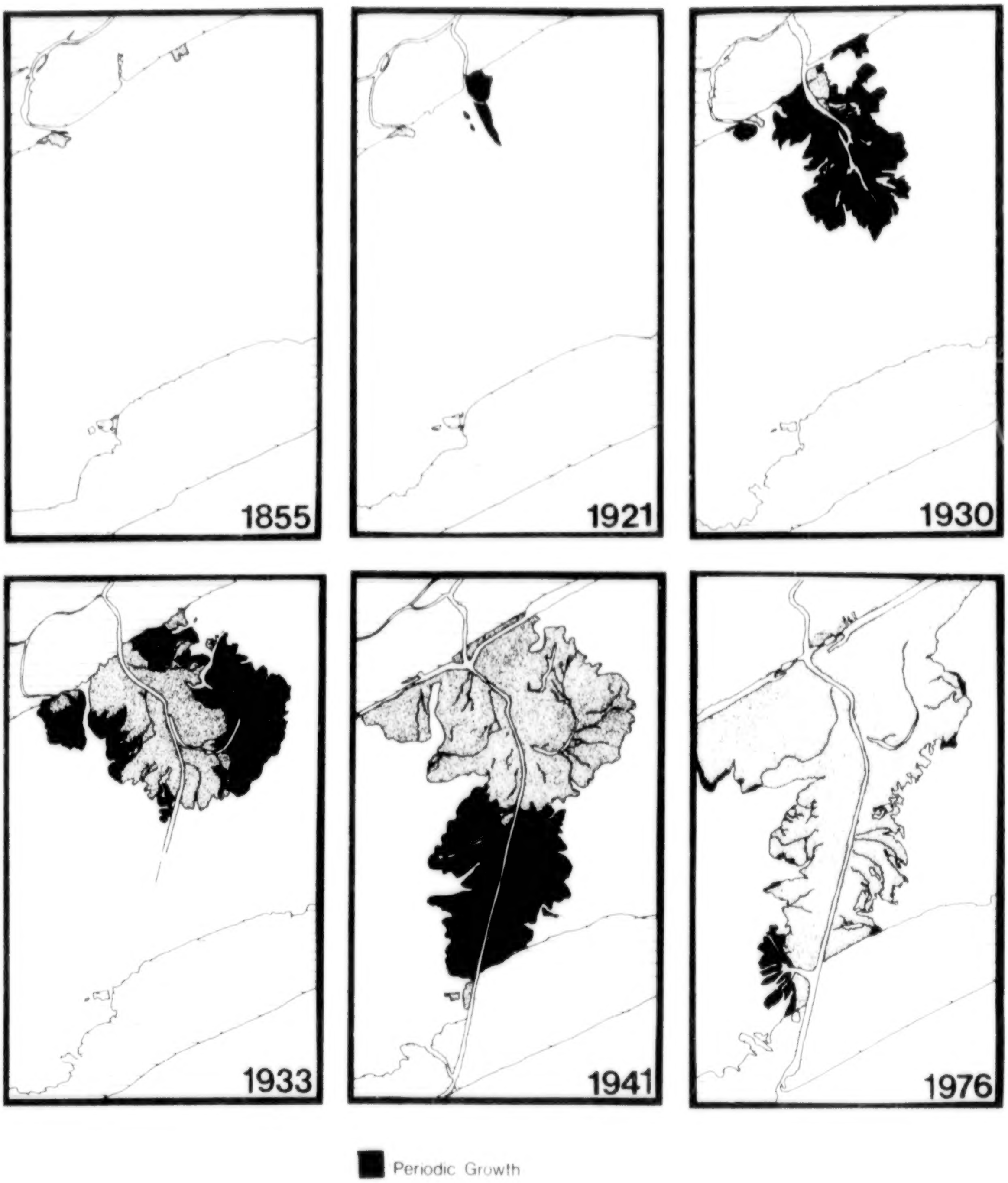


Figure 2. Delta development of Colorado River under influence of channelization.

sediment introduction played a major role. To evaluate this aspect a study was conducted to determine the extent and geomorphic characteristics of future delta growth (van Beek et al. 1980). Through analysis of discharge and sediment load characteristics of the Colorado River, numerical modeling of bay circulation, and application of delta growth concepts, it was estimated that future delta development would occur at an average annual rate of 40 acres (16 ha). This rate of development is contingent upon one or more years of rapid subaerial delta growth during major floods alternating with longer periods of mainly subaqueous growth. The prediction was based on an estimated average retention of 7 percent of the delivered sediment.

The proposed plan provides for management of initial delta growth through utilization of spoil from the diversion channel (Figure 1). Elevations and distribution of the spoil correspond as closely as possible to natural deltaic deposition in order to encourage development of wetland habitats on the spoil substrate and to guide initial distributary development.

Analysis of historic delta growth under natural conditions and estimates of future salinities allowed further prediction as to habitat distribution. Of the predicted subaerial delta complex, approximately 80 percent is estimated to be composed of productive estuarine habitats, including distributary channels, embayments, and low marsh, serving the juvenile stages of many of the commercially important fish and shellfish species.

Benefits to bay and offshore commercial fisheries as a result of freshwater inflow and delta building were estimated at $10,000,000 annually as a result of expected increases in harvest, primarily of white shrimp (USACE 1980). Calculation of these benefits was based to a large extent on the increase of the wetland/open water ratio for Matagorda Bay. Against this perspective let us examine the projects affecting the use of fresh water and sediment from the Atchafalaya River.

LOWER ATCHAFALAYA RIVER PROJECT

Approximately 30 percent of the fresh water and sediments delivered to Louisiana by the Mississippi River is directed through the Old River Control Structure into the Atchafalaya River (Figure 3). Following partial retention of the coarser load within the floodplain system, this water and the remaining sediments (nearly 80 percent) are discharged into the Atchafalaya-Vermilion estuary where they have initiated development of a potentially major delta complex. Discharges enter Atchafalaya Bay through two channels: the Lower Atchafalaya River and the Wax Lake Outlet (Figure 3). Of these two channels, the Lower Atchafalaya River is the more important, carrying an average of 65 percent of the discharge and 73 percent of the sediment load.

LOWER ATCHAFALAYA RIVER

Initially related to fisheries and subsequently to offshore oil production, the Lower Atchafalaya River also has increasingly served navigation. For this purpose, a navigation channel across Atchafalaya Bay was initiated by dredging

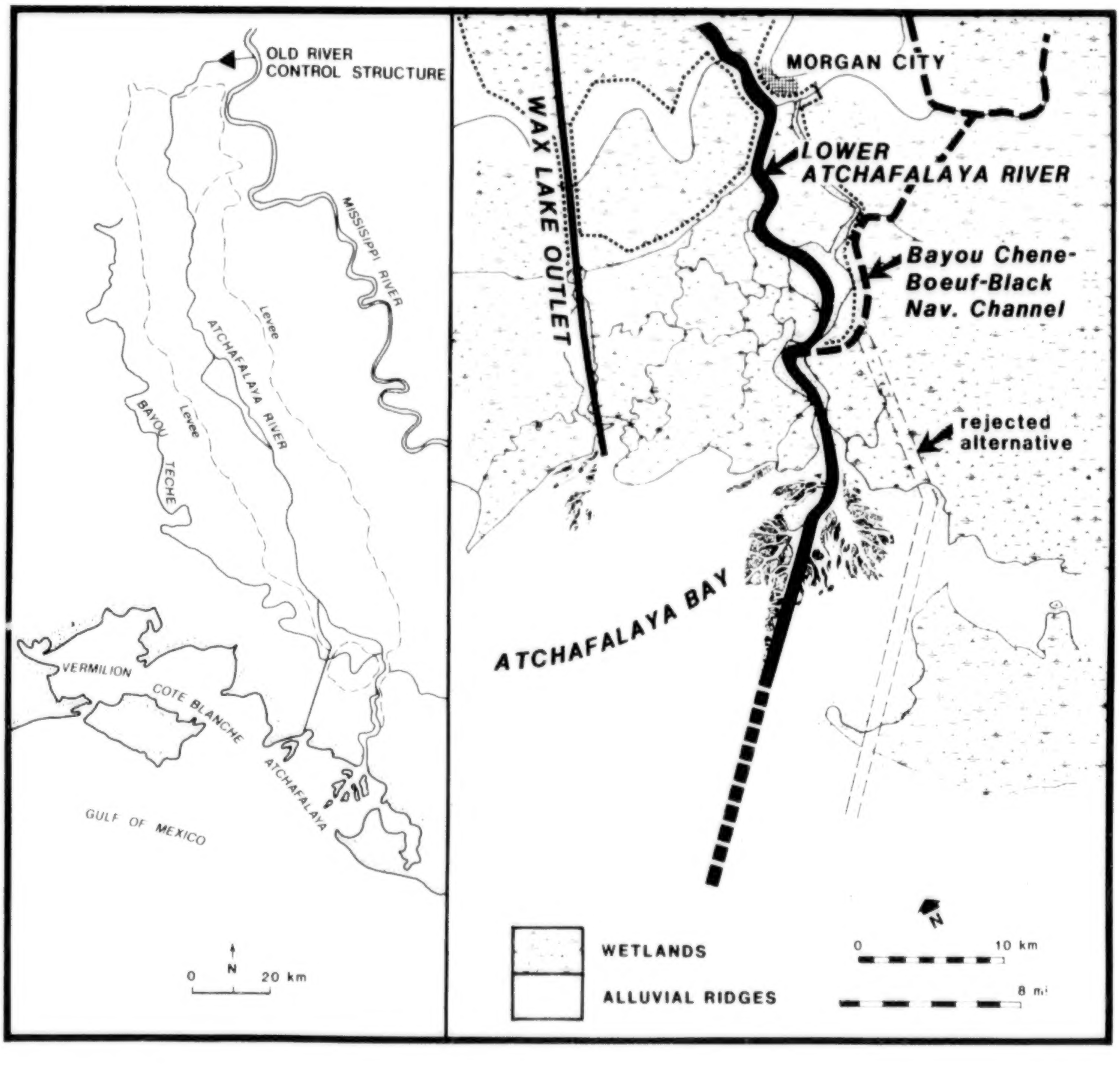


Figure 3. Atchafalaya River Basin and Lower Atchafalaya River navigation project.

in 1910, with subsequent enlargements until authorized dimensions (200 by 20 ft or 60 by 6 m) were nearly achieved in the 1960's. In 1968, a new authorization was obtained to further enlarge to 400 by 20 ft (120 by 6 m) the navigation channel across Atchafalaya Bay, as well as Bayous Chene, Boeuf, and Black and Avoca Island Cutoff Channel (Figure 3), for the purpose of facilitating transport of offshore platforms for oil production. Enlargement of the navigation channel was favored over the alternative of separation of navigation from the Lower Atchafalaya River as shown in Figure 3.

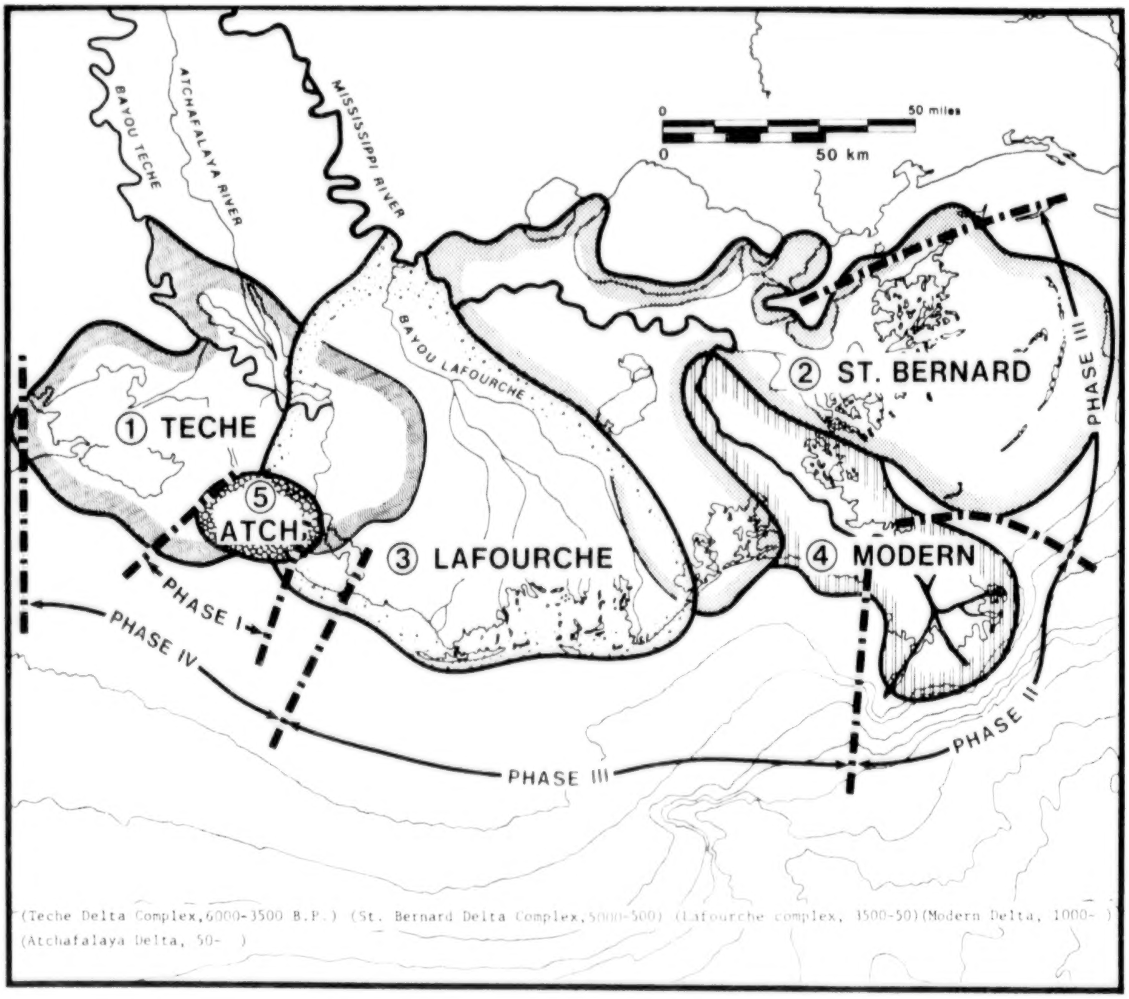
The navigation channel through the bay increasingly alters the dispersion and deposition of sediments delivered through the Lower Atchafalaya River and, thereby, the future function of the Vermilion-Atchafalaya estuarine complex as part of the Mississippi River deltaic plain system. This concerns in particular development of the Atchafalaya River delta complex, but also eventually involves the introduction of fresh water and sediment into adjacent estuarine systems.

MISSISSIPPI RIVER DELTAIC SYSTEM

Even though full diversion of the Mississippi River into the Atchafalaya River course has been prevented by the Old River Control Structure, the importance of the Atchafalaya River as part of the Mississippi River deltaic system can be easily demonstrated when considering the process through which that system and its associated resources have been perpetuated in the past.

Development of the diverse and biologically extremely productive Mississippi deltaic system (Figure 4) has been the result of the lagged, cyclic development of individual delta complexes associated with successive upstream diversions similar to that of the Atchafalaya River (Frazier 1967). The succession in each delta cycle, as illustrated schematically in Figure 5, is governed by three major sets of processes: the introduction of fresh water and sediment; the subsidence of the area and the compaction of sediments; and the combined action of waves, tides, and currents which redistributes the deltaic sediments and, together with freshwater inflow, governs salinity. With the cyclic change of a delta complex comes a change in its natural environments (Gagliano and van Beek 1975). Since individual cycles are lagged in time and occur at different locations, any particular environment is present at some time within each of the delta complexes. The sequential cycling of the deltas thus insures continuous maximum diversity of the delta system as a whole as long as the process of shifting delta development is allowed to continue.

With confinement of two-thirds of Mississippi River flows for navigation and flood protection purposes, and with extension of the river to a point where further delta growth has halted, two-thirds of the river's direct contribution to maintenance of the deltaic system has been eliminated. The delta cycle, as illustrated in Figure 5, predicts gradual disintegration of all those parts of the coastal area that have been severed from the flow of water and sediment provided by the Mississippi River. Presently attained phases in the cyclic development of individual complexes have been indicated in Figure 4.



(Teche Delta Complex,6000-3500 B.P.) (St. Bernard Delta Complex,5000-500) (Lafourche complex, 3500-50)(Modern Delta, 1000-)
(Atchafalaya Delta, 50-)

Figure 4. [illegible]ntial development of Mississippi River deltaic plain and phases in the cycles of individual delta lobes (see Figure 5).

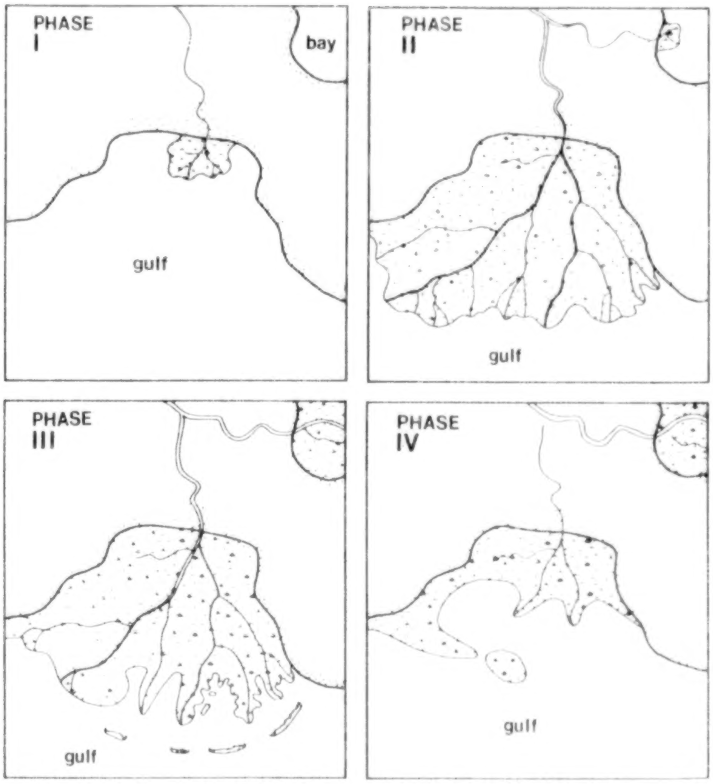


Figure 5. Phases in the cycles of a Mississippi River delta lobe.

Thus, development of a new delta complex at the mouths of the Atchafalaya River is the only physical development that continues the natural process by which the deltaic plain and its diversity and biological productivity are maintained. The importance of this becomes increasingly evident with the realization that only 30 percent of the Mississippi River flows and sediments arrive through the Atchafalaya River. Maximum utilization of these resources is therefore imperative.

ATCHAFALAYA DELTA DEVELOPMENT

It was not until the 1950's that sediment contribution to Atchafalaya Bay became of sufficent volume and such grain-size composition that deposition began to take place at the mouths of the Lower Atchafalaya River and Wax Lake Outlet (Shlemon 1972). This increase related directly to reduced sediment retention within the Atchafalaya River Basin as lacustrine deltas replaced lakes, and the Atchafalaya River Channel became increasingly confined and subject to scour. Greater efficiency of the Atchafalaya River to transport its load, together with the added sediment through channel development, increased both the volume and the grain size of sediments reaching the bay.

As documented by USACE bathymetric surveys, sequential aerial photography, and bottom cores (Cunningham 1981, Roberts et al., 1980, Rouse et al. 1978, van Beek et al. 1977), the result of the influx of sediments was initially the rapid development of a subaqueous platform that extended from both channel mouths across Atchafalaya Bay and into adjacent bays. Subaqueous development was followed by emergence and growth of subaerial delta lobes during the extreme flood years of 1973, 1974, and 1975. At present, the Lower Atchafalaya delta complex extends over a 15.1-mi^2 (39.1-km^2) area including exposed and intertidal habitats and associated distributary channels (Figure 6).

NAVIGATION MAINTENANCE

Increasing sedimentation in the bay also necessitated an increased dredging effort to achieve and maintain authorized dimensions of the navigation channel. To provide for at least partial confinement of flows and aid in channel development, dredge spoil from maintenance and enlargement has been placed on the west side of the navigation channel (Figure 6); on the east side partial confinement is provided by emergent deltaic deposits.

With delta progradation, the need for channel dredging and spoil disposal has been extended progressively seaward. At present, emergent spoil deposits extend as far as the Point au Fer shell reef at the seaward boundary of the bay. The dredging increasingly involves a circular chain of events in that flow confinement promotes delta progradation which, in turn, requires channel extension resulting in spoil disposal and further confinement. Accordingly, further development and maintenance of the navigation channel in the present manner should be assessed with regard to future delta growth.

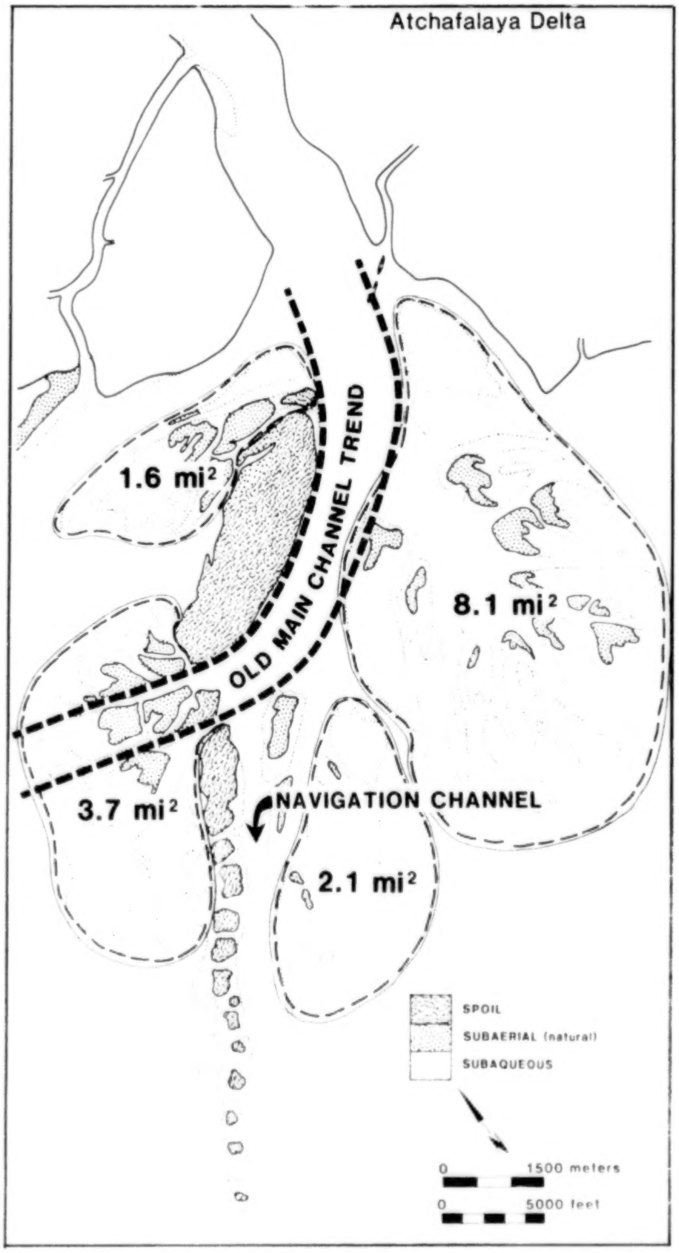


Figure 6. Lower Atchafalaya River delta and navigation channel.

DELTAIC PROCESSES

Maximum subaerial delta growth is achieved by retention of the largest possible volume of sediments in shallow water. Such retention occurs through a number of interactive hydraulic and sedimentary processes that have been extensively described (Axelsson 1967, Russell 1936, Welder 1959). Most important among these are channel bifurcation, natural levee building, and crevassing (Figure 7). Channel bifurcation, resulting from bar development at the channel mouths, provides for the development of major divergent distributaries and the ensuing hierarchical building of individual delta lobes. Associated with the development of the distributary channel network is the building of natural levees which provide a protective skeleton facilitating retention of fine-grained sediments in the interdistributary embayments. Crevassing, or the development of overflow channels, occurs when the hydraulic gradient increases between distributary channels and adjacent or interdistributary areas as a result of partial flow confinement between natural levees. This process appears most active during initial delta development, as illustrated in the eastern Atchafalaya delta lobe, and contributes significantly to widening of the natural levees and initial infilling of the interdistributary basins.

Expansion of the delta through distributary development and crevassing is dependent on hydraulic gradients between channels and adjacent water bodies. The larger the gradient, the greater can be the length and dimensions of the developing distributary or crevasse channel without loss of sediment transport ability. This appears to be reflected in the natural delta system at various levels of the hierarchy by the relationship between width of individual distributary channels and average radial extent of associated sedimentation (Figure 8). As illustrated by comparison of the Atchafalaya River delta and Mississippi River delta, this relationship is maintained as the delta matures and distributary channels tend to become narrower and more confined by natural levee aggradation.

EFFECTS OF THE NAVIGATION CHANNEL

Modification of the major deltaic processes by the navigation channel and associated spoil deposits is believed to result in delta development falling significantly short of its potential. Development to the west has been severely limited by spoil disposal. This has forced sediment either seaward or eastward where sediment retention is adversely affected by net seaward tidal flows (van Beek et al. 1977). Much of the sediment retained by dredging has been disposed at elevations that preclude development of wetlands on the spoil substrate. Most important, however, is that delta progradation is being forced progressively seaward along a single major channel and into marine waters where decreased sediment retention and greater water depth reduce subaerial development, That such is the case is further indicated by the relatively low retention of sediments in Atchafalaya Bay. Comparison of sediment input and total deposition within Atchafalaya Bay for the period of 1967-1977 indicates retention of less than 30 percent. This is well below the average 70 percent calculated for Mississippi River subdeltas (Gagliano and van Beek 1976).

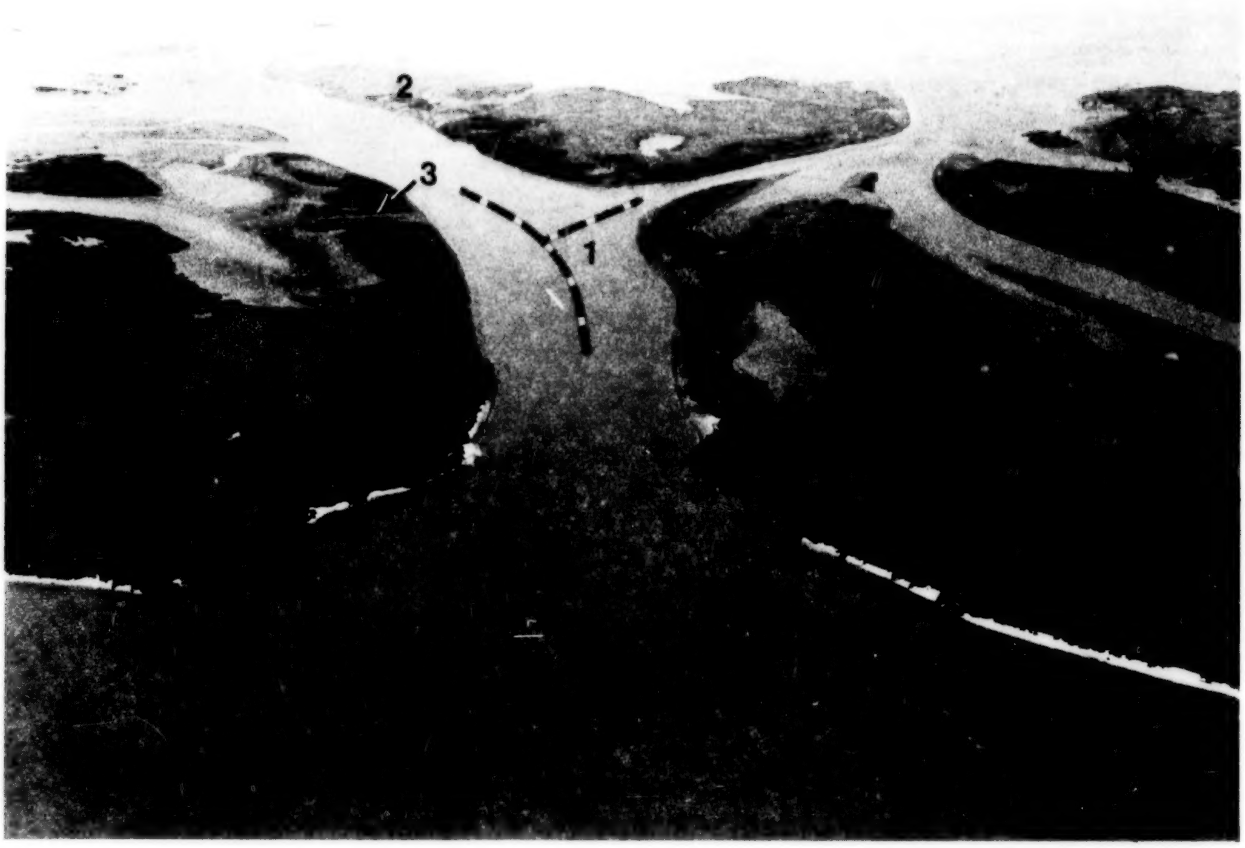


Figure 7. Delta growth associated with distributary channel extending westward through spoil banks of navigation channel (1. bifurcation, 2. natural levee, 3. crevasse).

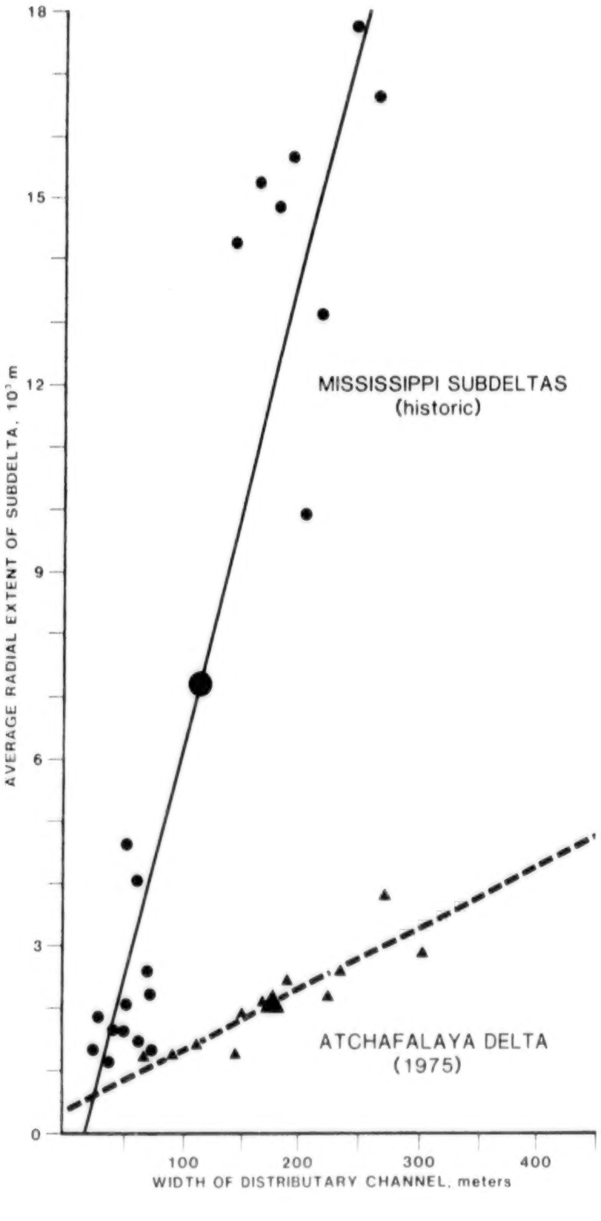


Figure 8. Relationships between widths of distributary channels and extent of associated subaerial delta development.

Specific causes may be identified. First of all, bifurcation of the main channel is limited to a single occurrence resulting in the eastern subdelta lobe. U.S. Geological Survey (USGS) 1937 bathymetry shows the natural trend of main channel development to have been curvilinear, coincident with the upper navigation channel and extending westward beyond the present spoil area (Figure 6). This trend was aborted as the navigation channel increasingly diverted flows seaward and the westward channel was largely blocked by spoil. Only two small distributaries remain, producing the only significant subdelta to the west of the navigation channel.

Further bifurcation of the main channel and distributary development is inhibited by maintenance. The dredging of the linear channel limits necessary shoaling and bar development, while flow preference for the more efficient navigation channel will favor abandonment of natural distributaries were bifurcation to occur.

Spoil deposits function as a natural levee, with gaps serving as overflow channels that aid in widening of the "levee." As in the natural delta, the majority of these channels must be expected to be short-lived and closed by overbank deposition. Those remaining are likely to be narrow and allow only a correspondingly limited extent of delta development (Figure 8).

In the absence of spoil, limitations of delta building have been much less in an eastward direction. However, it has been noted that hydraulic efficiency in that direction is decreasing, as indicated by shoaling of distributary channels (van Heerden 1980) and no significant growth following the above average 1979 flood. Possibly this is accounted for by a decreasing hydraulic gradient as the open water area available to accommodate river discharge and tidal flow from adjacent marshes declines in area.

The perceived effects of channel maintenance and spoil disposal are generally verified by four series of discharge and suspended load measurements made during 1980 flood conditions (Figure 9). These measurements show approximate proportional distribution of flow and suspended sediment. In all cases, the largest proportion of flow and sediment continues along the navigation channel. Approximately 25 percent is diverted into the main eastern subdelta. Subtraction indicates that up to 25 percent may be diverted through multiple distributaries into the southeastern quadrant of the delta and seaward. Only 15 percent is allowed toward the east, mostly through the two restricted distributary channels below the major spoil island. Flow through remaining spoil gaps never exceeded 1 percent. Nearly one-quarter of the sediments is channeled directly seaward by the navigation channel.

While future flow confinement may set the stage for a major crevasse and distributary development in a westerly direction, no such development is insured. Without adequate delta management, it is likely that further maintenance and development of the navigation channel will increasingly capture the main flow. This fixation will continue to limit distributary development and preclude future shifting of the main channel as necessary to maintain the delta systems. That

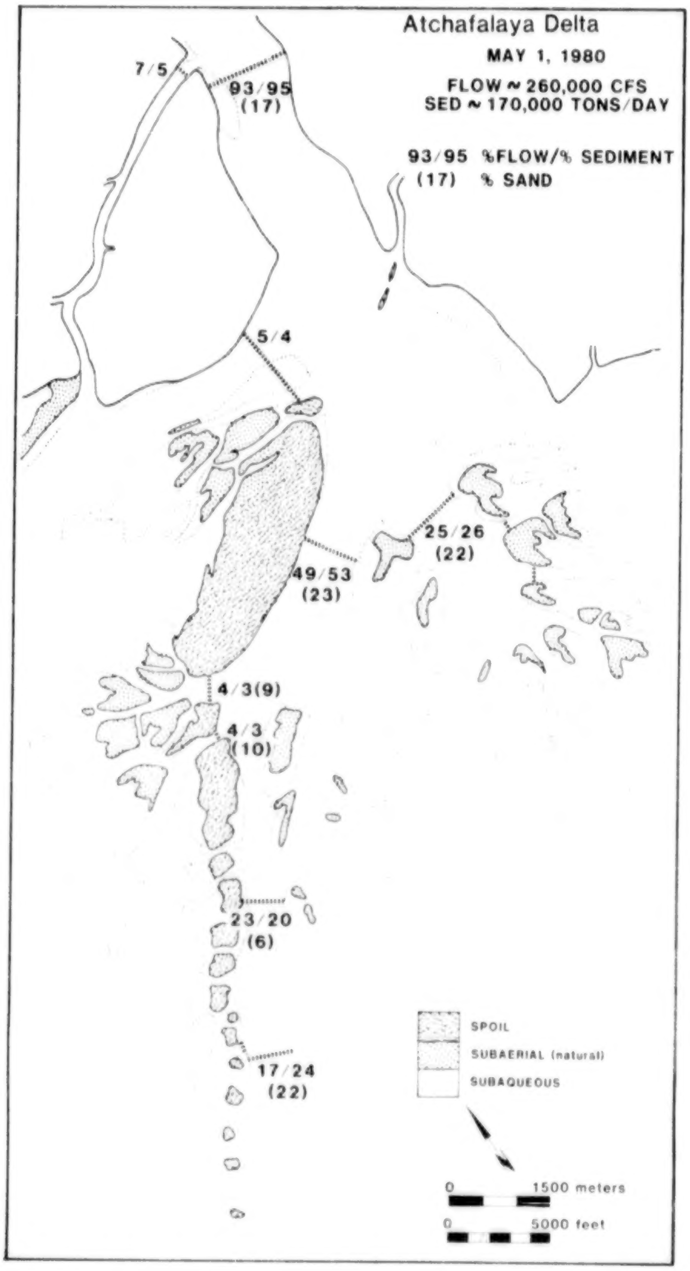


Figure 9. Distribution of flow, suspended load, and sands (as percentage of suspended load) in the Lower Atchafalaya River delta.

necessity arises from the short life span of individual delta lobes as a result of not only abandonment of major distributaries in combination with subsidence and wave erosion, but also of progressively greater confinement of flows and sediments by existing distributaries. Such development is well illustrated in the active Mississippi River delta.

Limitations on delta growth associated with the Lower Atchafalaya River become of further consequence when considering the limited advance of the Wax Lake delta. While discharges through Wax Lake are about half of those through the Lower Atchafalaya River, sediment load is only one-third. In addition, sands make up a much smaller percentage of the load which reduces development of a stabilizing skeleton of natural levees. With pending plans for reduction of Wax Lake Outlet discharges, even more sediment could be diverted to the Lower Atchafalaya River.

PROJECT COMPARISON

Comparison of the Colorado Rivver and Lower Atchafalaya River projects raises some serious questions. Considered from a navigation point of view, sediment is an obvious liability. Yet in the same year, 1968, two navigation projects were authorized that accomplished opposite results. At the Colorado River mouth, the project provides for separation of navigation and river flow to negate adverse effects of sedimentation. At the Lower Atchafalaya River, channel enlargement is provided for in an area of increasing sedimentation and in a manner that increasingly attracts river flow and sediments.

Considered from a fish and wildlife point of view, projects are equally conflicting. Diversion of the Colorado River into Matagorda Bay is considered to generate sufficient benefits, largely through development of new wetlands and flows routed through those wetlands, to warrant implementation solely as an environmental enhancement project. Benefits are sufficient to provide for spoil disposal in a manner that enhances wetland development and preserves existing wetlands.

At the Lower Atchafalaya River, separation of navigation and the river channel was rejected as an alternative on the basis of not providing additional benefits over the present project and having greater adverse effect on fish and wildlife resources. These adverse effects related primarily to loss of marsh along a 5-mi (8-km) segment of the separate navigation channel.

While it may be argued that the Colorado River Project is reassessed on the basis of present day values and the Lower Atchafalaya River Project started ten years ago, there are several reasons why this should not be an excuse to proceed with the latter project without reevaluation. First, the project is far from completion, the 20-ft (6-m) contour being located 15-mi (24-km) into the Gulf of Mexico and maintenance being a constant requirement. Second, the opportunity for reevaluation and redirection of the project presently exists under the Atchafalaya Basin Land and Water Resources Study. Third, and most important, optimum use of Atchafalaya River water and sediment is imperative to offset accelerating loss of wetlands and to maintain part of the Mississippi

River deltaic plain as a resource complex serving man as well as fish.

While it is recognized that the question of whether sediments should be considered a liability or an asset has a different answer based on perspective and interest, these answers should be at least consistent when viewed from the same point of view.

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LOSS OF COLORADO RIVER INFLOWS TO MATAGORDA BAY, TEXAS AND EFFORTS FOR RESTORATION

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ABSTRACT

Major disturbances to the Matagorda Bay system, including diversion of the Colorado River to the Gulf of Mexico and loss of supporting marshes, are discussed. Supporting marshes have been reduced from 18,623 ha (46,000 acres) to 15,789 ha (39,000 acres) and oyster reefs have been reduced in area from 11,660 ha (28,800 acres) in the late 1800's to 8,291 ha (20,480 acres) at present with only one-fourth of this area consistently productive. Production of shellfish in West Matagorda Bay is estimated to be only 20 percent of that possible through utilization of environmental management. Methodologies for calculating potential changes in shellfish production due to re-diversion of the Colorado River are presented. Annual economic benefits for increased shellfish production in West Matagorda Bay and Gulf of Mexico attributable to rediversion are estimated to be in excess of $17.1 million. Significant actions relating to the Mouth of Colorado River Texas Project, sanctioned by Section 101 of the Rivers and Harbor Act of 1968, include separation of project features by the Corps of Engineers, restoration of the diversion feature to the project, and delay in navigation feature construction due to threats of legal action. A project to link East Matagorda Bay to the Colorado River Channel is suggested.

INTRODUCTION

The Matagorda Bay System is the second largest in Texas, comprising 21 percent of the total area and about 25 percent of the volume of Texas estuarine waters. The Matagorda Bay system ranks third among Texas bays in value of commercial seafood landings. However, it could be considerably more productive. Man-caused perturbations have induced a decline in the bay's biological production and economic output.

The mechanism to restore productivity and increase economic output has existed since 1968, via the U.S. Army Corps of Engineers' Mouth of Colorado River Project. Authorized in Section 101 of the River and Harbor Act of 1968, the project is unique in its opportunity to greatly restore and benefit the natural ecosystems, environmental quality and related economics through its diversion feature;

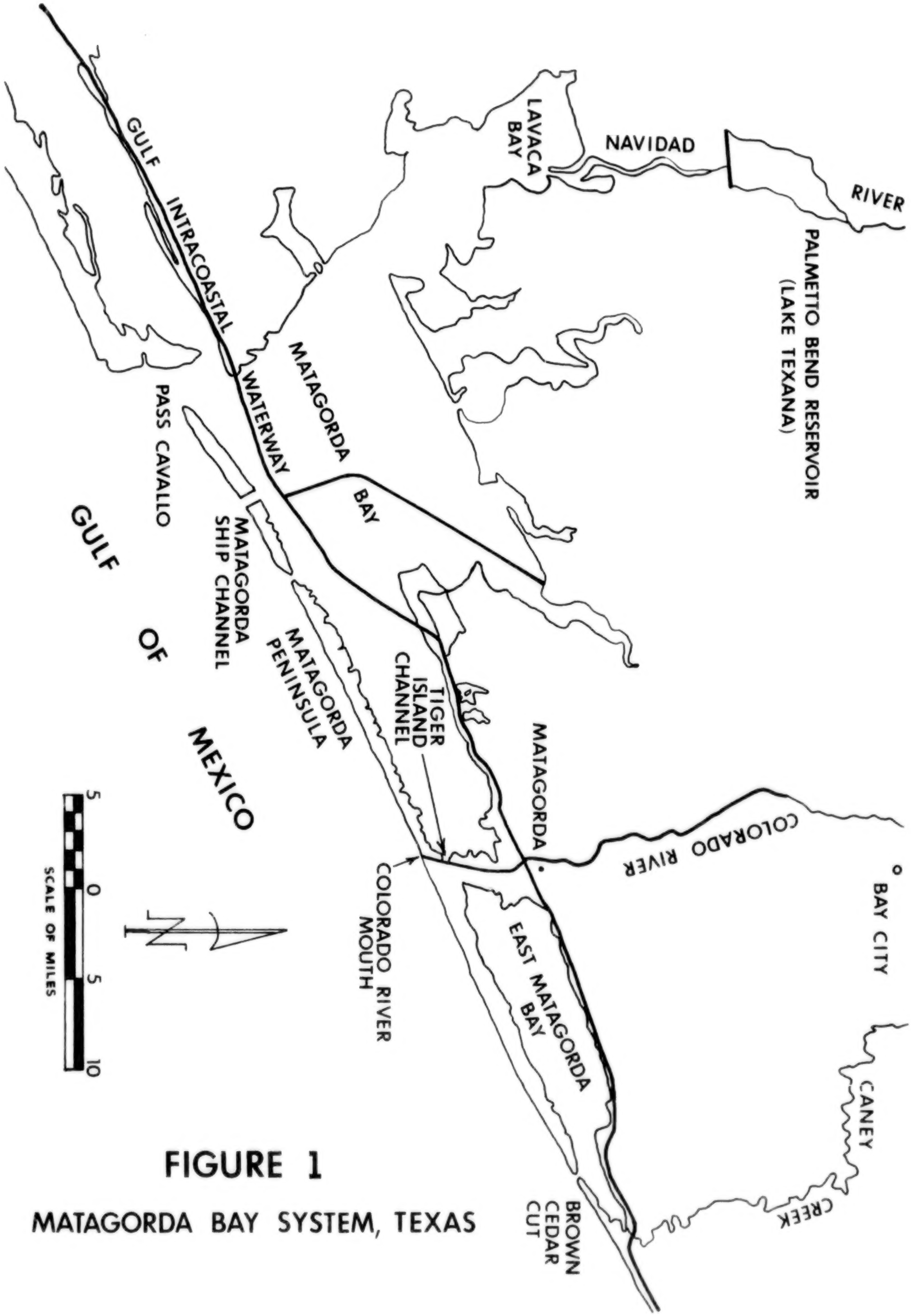

FIGURE 1

MATAGORDA BAY SYSTEM, TEXAS

and benefit local municipal, industrial and agricultural activities through its navigation feature. The diversion feature would reintroduce Colorado River flows into western Matagorda Bay. The navigation feature would improve the lowermost seven miles of the river for waterborne shipping by enlargement of the river channel and construction of jetties at the river mouth to control shoaling.

In moving to implement the project, the Corps of Engineers proposed to construct only the navigation feature until public, private, and commercial fishing entities protested, threatened litigation, and influenced revival of the diversion feature.

PERTURBATIONS

Major disturbances occurring since 1929 which have reduced the biological production of Matagorda Bay in descending order of magnitude are: (1) diversion of the Colorado River flow from Matagorda Bay to the Gulf of Mexico in the mid-1930's; (2) construction of the Gulf Intracoastal Waterway in the 1940's; (3) periodic spoiling from navigational channel maintenance shell dredging, etc.; (4) water development and diversion in the river basin above the estuary since the 1930's and (5) removal of a major log jam in the river near Bay City, Texas in 1929 (U.S. Fish and Wildlife Service 1979).

DIVERSION/LOG REMOVAL

Before 1929, the Colorado River flowed directly into Matagorda Bay near the town of Matagorda, Texas (Texas Department of Water Resources 1978b). Removal of a large log jam above the town by dynamiting resulted in sudden downstream transport of great quantities of naturally trapped silt and subsequent unnatural, rapid formation of the present delta (Bouma and Bryant 1967). Productive bay bottom was inundated, highly productive oyster reefs destroyed, and the eastward arm of Matagorda Bay was divided into two separate water bodies. By local action the delta was channelized and Matagorda Peninsula breached so that the Colorado River was diverted from the bay, through the delta channel, and directly into the Gulf of Mexico. The delta, about 1,619 ha (4,000 acres), divided Matagorda Bay into what are now known as East Matagorda Bay and West Matagorda Bay. The east bay was segregated from Pass Cavallo, the historical natural outlet to the Gulf of Mexico. Today, the east bay intermittently connects with the gulf through a hurricane "blowout" channel called Brown Cedar Cut. Periodically the cut is opened by dredging but it recloses by littoral drift. Widely fluctuating salinities ranging up to 38 ppt (Bouma and Bryant 1967; Texas Game and Fish Commission 1957) occur in East Matagorda Bay due to inadequate freshwater inflow and water exchange with the gulf. When Brown Cedar Cut is closed, migrating marine organisms must follow a circuitous route, entering the eastern portion of the bay via the Gulf Intracoastal Waterway.

Gunther et al. (1973) emphasized that fresh water and nutrients formerly entering Matagorda Bay now pass directly to the Gulf of Mexico. The Colorado River delta marshes are now not subject to inundation and flushing by Colorado River flows except during extreme hydrological events (Texas Department of Water Resources 1978b), therefore the value of the delta for nutrient input to the bay is minimized. Some Colorado River flows now enter West Matagorda Bay through Tiger Island Cut (an abnormally positioned man-made waterway). However, studies by the Texas Department of Water Resources (1978 a) suggest that during periods when the mouth of the Colorado River at the gulf is not plugged by shoaling, 75 percent of riverborne nitrogen, phosphorus and organic carbon pass directly to the gulf. Erratic flows and abnormal circulation patterns result from tidal and river flows through Tiger Island Cut. Salt water from the gulf intrusion into West Matagorda Bay via Tiger Island Cut occurs when river flows are not sufficient to push back the saltwater wedge.

GULF INTRACOASTAL WATERWAY

Construction of the Intracoastal Waterway along the north edge of the east arm of Matagorda Bay, and attendant maintenance spoiling has disrupted a significant portion of the bay-mainland marsh interface creating a barrier to exchanges between the bay and over 4,450 ha (11,000 acres) of formerly supporting wetlands. The importance of estuary-marsh interface (edge) to productivity of estuaries has been extolled by Gucinski (1978), Valiela and Teal (1974) reported by Gucinski (1978), and Turner (1977).

DREDGING

In the Lavaca-Matagorda estuary complex over 27,200 ha (17,900 acres) of bay bottom and associated lands have been disturbed by dredging and spoiling (McGowen et al. 1976a, 1976b). McGowen et al. (1976a), stated that redistribution, reworking and erosion of dredged spoil (by the operation of aeolian and lotic processes) is a major source of lotic sediment. The U.S, Army Corps of Engineers (1977a) recognized that high turbidity of Matagorda Bay and lack of available nutrients inhibit phytoplankton productivity.

UPSTREAM WATER DEVELOPMENT

Reservoir development and diversions in the upper Colorado River Basin have reduced the amount of fresh water and nutrients available to the bay and altered the salinity regime (Gunter et al. 1973). The average annual discharge (1899-1936) of the Colorado River at Austin prior to regulation by upstream reservoirs was 2.4×10^9 m^3 (1,964,000 acre-feet) but has fallen to 1.85×10^9 m^3 (1,499,000 acre-feet) per year (1937-1977) following regulation by upstream reservoirs and increased water usage (U.S. Geological Survey 1978). Current average discharge records (period after regulation began) indicate that below Austin discharge builds to 2.69×10^9 m^3 (2,179,000 acre-feet) at the Columbus gage but falls off to 2.22×10^9 m^3 (1,795,000 acre-feet) at the Bay City gage due to diversions primarily for irrigation (U.S. Geological Survey 1978). Estimated West Matagorda Bay salinity with and without diversion of full Colorado River flows to West Matagorda Bay are shown in Table 1. In 1977, the Fayette power plant required nearly 5.92×10^7 m^3 (48,000 acre-feet) of water from the Colorado River. The South Texas Nuclear Project, soon to be in operation, is authorized to

TABLE 1. Estimated West Matagorda Bay salinity (Shanker and Masch, 1970)

Annual Climatic Conditions	Matagorda Bay Salinity (0/00) Without Colorado River Flows	With Colorado River Flows
Wettest (1941)	21	15
Average High (1940-46)	24	20
Average	28	24
Average Low (1950-56)	33	30
Driest (1956)	38	35

TABLE 2. Ratio of shellfish to oyster production in Matagorda and San Antonio Bays, 1962-1976.

Shellfish	Ratio of Shellfish to Oysters Matatorda Bay	San Antonio Bay
White shrimp	4.2:1	2.6:1
Brown shrimp	1.0:1	1.0:1
Blue crab	3.2:1	3.2:1

divert 1.26×10^8 m^3 (102,000 acre-feet) per year from the River. Municipal uses in the Austin Metropolitan Area are increasing at an accelerated rate and an additional reservoir in the upper basin has been approved by the Texas Water Commission. The Colorado River Municipal Water District has been granted a permit to build the 6.84×10^8 m^3 (554,340 acre-feet) capacity Stacy Reservoir and divert 1.39×10^8 m^3 (113,000 acre-feet) per year for municipal and industrial purposes. These diversions will not only affect the salinity of Matagorda Bay, but also reduce the capacity of the river to transport sediment and nutrients.

The Palmetto Bend Reservoir will also have significant effects on West Matagorda Bay. This reservoir, which is near completion, will reduce estuarine inflow to the bay by an average of 1.13×10^7 m^3 (92,000 acre-feet) per year, and reduce sediment input to the Lavaca River Delta by 49 percent (U.S. Bureau of Reclamation 1974). The final environmental impact statement for Palmetto Bend Reservoir indicated reliance on the Mouth of Colorado River Project to partially mitigate losses caused by Palmetto Bend Reservoir.

MOUTH OF COLORADO RIVER PROJECT

The Mouth of Colorado River Project, Texas was authorized by the River and Harbor Act of 1968 and described in Senate Document No. 102 (90th Congress, 2d. Session). Project purposes are navigation, flood control, enhancement of fish and wildlife, and recreation development. The diversion feature benefit-cost ratio was calculated to be 4.9 to 1 while the navigation feature benefit-cost ratio was only 1.03 to 1. The Bureau of the Budget expressed concern with the marginal justification of the navigation feature. The diversion feature was strongly supported by the Bureau of Sport Fisheries and Wildlife and Texas Parks and Wildlife Department. Matagorda County Navigation District No. 2, local sponsor of the project, pledged to provide local cost sharing including diversion costs.

The draft environmental statement for the project (U.S. Army Corps of Engineers 1976) omitted the diversion feature. Despite protests from the U.S. Fish and Wildlife Service, the National Marine Fisheries Service and the Texas Parks and Wildlife Department, a final environmental impact statement was circulated on the navigation feature only, and failed to include state agency comments.

The Corps of Engineers preferred to abate the diversion feature and have its implementation contingent upon additional assessments of diversion's ecological impacts. Of major concern to the Corps was the effect of sedimentation expected to occur from reintroduction of the river into Matagorda Bay. Local interests were concerned about meeting costs sharing requirements and hazard to fishing equipment from inflow of debris to the bay. Concurrent economic gains from diversion were not thoroughly developed at that time.

There was strong opposition by natural resource entities to splitting the Mouth of Colorado River Project into staged implementation, and implementing the least cost-effective, least environmentally sound feature (navigation) first.

To alleviate the discord, former Congressman John Young (14th District of Texas) introduced H.R. 12308 on April 24, 1978 to secure 100 percent federal funding of the diversion feature. The legislation was not enacted.

PRIVATE EFFORTS

Following circulation of the final environmental impact statement, private conservation organizations strongly sought concurrent construction of navigation-diversion, or construction of diversion first. The Texas Shrimp Association worked closely with Congressman Joe Wyatt, successor to Congressman Young, to pursue total Federal funding of diversion.

After failure to secure commitment from the Corps of concurrent construction of the diversion and navigation features, the Wildlife Management Institute sought, and obtained, Environmental Protection Agency and Council on Environmental Quality action. Action was sought under the National Environmental Policy Act of 1969, on the grounds of separation of interrelated project features and lack of State agency comments in the final environmental impact statement.

The Texas Environmental Coalition, Outdoor Nature Club and Audubon Society in Houston, Texas, Sierra Club, Texas Shrimp Association, National Wildlife Federation, Wildlife Management Institute, and others requested a public hearing to address Section 404 (Federal Water Pollution Control Act 1972, as amended) implications from the Project. On April 30, 1979 the Corps of Engineers held the hearing at Bay City, Texas. The National Wildlife Federation was represented by a legal intern who spoke for their affiliate Sportsman's clubs of Texas. The Gulf Coast Fisherman's Environmental Defense Fund, National Environmental Defense Fund, and Natural Resources Defense Council submitted written support for implementation of the diversion feature.

On May 19, 1979, the Lone Star Chapter of the Sierra Club adopted a resolution regarding initiation of legal action if construction of navigation preceded diversion. Subsequently, the Corps of Engineers postponed construction of the navigation feature pending circulation of a general design memorandum and environmental impact statement on the diversion feature (U.S. Army Corps of Engineers 1980). The Corps, U.S. Fish and Wildlife Service, and National Marine Fisheries Service cooperated to produce the dual memorandum-environmental statement document, which was circulated in April 1980.

The document recommends construction of diversion and closure of Tiger Island Cut. A special evaluation (van Beek 1980) is contained in the document which alleviates purported concerns about excessive delta formation from rediversion of the river into the bay. Benefits from rediversion are set by the Corps at $9.4 million annually. While the information about delta formation generally supported recommendations previously made by the fish and wildlife agencies, there was a 45 percent downward adjustment in economic benefits from those developed by the Fish and Wildlife Service in 1979 (U.S. Fish and Wildlife Service 1979), which set annual benefits at $17.1 million.

U.S. FISH AND WILDLIFE SERVICE REPORT

Early in 1979, the U.S. Fish and Wildlife Service, National Marine Fisheries Service and Texas Parks and Wildlife Department cooperated in re-evaluating their previous Mouth of Colorado River reports to the Corps of Engineers. The resulting study and supplementary report (U.S. Fish and Wildlife Service 1979) emphasized ecological impacts from delta marsh accretion, and re-evaluated economic implications associated with certain fisheries. Detailed research which would provide economic and ecologic data for the Matagorda system, and other Texas estuaries, had been implemented by the Texas Department of Water Resources and U.S. Fish and Wildlife Service. The research was necessarily long-range, however, and not timely for the decisions about rediversion which were immediately at hand. The short time available for additional study and reporting, before approval of the final impact statement and beginning construction of only navigation, necessitated a study based on synthesis of published data and field checks. Findings of the 1979 study follow.

RESULTS AND DISCUSSION

DELTA ACCRETION

Matagorda Bay historically had about 18,600 ha (46,500 acres) of perimeter marshes (McGowen and Brewton 1975). Including the 1,619 ha (4,000 acres) delta and a small 138 ha (340 acres) alluvial fan at Tiger Island Cut, the estuary today is supported by only about 15,790 ha (39,000 acres) of perimeter marshes. The marshes are diminishing in area about 20 ha (50 acres) annually (McGowen and Brewton 1975). The Corps of Engineers (1977a) predicted that with full rediversion as much as 10,500 ha (26,000 acres) of delta marsh would develop in West Matagorda Bay in 100 years. Based on the study by van Beek (1980), the Corps has adjusted the figures down to 1,844 ha (4,500 acres) in 125 years.

Findings by the fish and wildlife agencies were that overall ecological production of the Matagorda estuary would improve as the delta accreted, and an adversely high amount of marsh would not occur. Prior to removal of the log jam from the Colorado River in 1929, the open water-marsh ratio of Matagorda Bay was approximately 6.1:1. Reattainment of that ratio was estimated to require 2,847 ha (7,000 acres) of marsh accretion. Gosselink et al.(1979) reported an open water-to-marsh ratio of 0.43:1 in the highly productive Chenier Plain on the Louisiana-East Texas coasts. Correll (1978) accumulated relevant ratios on a worldwide basis, and found a range of 3:1 to 4:1. For Matagorda Bay to attain comparable ratios 68,000 ha (168,000 acres), 23,411 ha (57,600 acres), and 13,511 ha (33,200 acres) respectively, of marsh would be required.

ECONOMIC EVALUATIONS

Brown shrimp (Penaeus aztecus), white shrimp (P. setiferus), blue crab (Callinectes sapidus), and American oyster (Crassostrea virginica), commercial species for which successive years of standardized harvest and economic data exists, were chosen for economic evaluation in the 1979 supplementary report. Other species in Matagorda Bay have significant commercial and recreational value (i.e., finfish; waterfowl; unusual and rare avifauna; furbearers) but were not included because of insufficient economic data on them. As a result, the 1979 estimate was kept conservative. Dollar values assigned to the species evaluated were the complete current published data (U.S. Department of Commerce 1976) at the time of study. An economic multiplier for Texas of 3.08 was adopted after Jones et al. (1974).

WEST MATAGORDA BAY FISHERY

Adequate records on shrimp and crabs were not available for the period preceding the major disturbances to Matagorda Bay. Reliable records on shrimp catch had been kept only since the late 1950's or early 1960's (O. J. Farley, J. H. Morgan, D. Moore pers. comm.). These records did not reflect a decline in shrimp production, but accurate determination could not be made of the amount of harvests because of variations in intensity of fishing effort, fishing gear utilized, and market demand for shrimp. A satisfactory line of records did exist, however for determining quantities of oysters. Stevenson (1891) reported that Matagorda Bay had a minimum of 11,660 ha (28,800 acres) of the finest oysters in Texas, and postulated that the good condition of oyster shells was largely due to great quantities of lime washed down from counties having limestone deposits above the estuary (Colorado River drainage). Moore (1907) estimated 1,768,000 kg (3,894,000 lb) of oyster meat from oysters 7.6 cm (3 inches) or greater in length were in the bay's eastern arm. Field observations made by the Texas Parks and Wildlife Department, National Marine Fisheries Service and the U.S. Fish and Wildlife Service in recent years indicated only one-fourth of the remaining 8,291 ha (20,480 acres) of oyster reefs (McGowen et al. 1976b) consistently support an oyster fishery. Examination of shells from Mad Island, Dog Island and Shell Island reefs gave evidence of loss due to oyster drill (Thais haemastoma) and oyster fungus (Labyrinthomyxa marina) infestations facilitated by periods of high salinity. Diener (1975) reported that only 103,512 kg (228,000 lb) of oyster meat were harvested from the bay in 1968. Current average annual harvest of oyster meat is approximately 114,000 kg (251,000 lb).

The literature revealed that water salinity in Matagorda Bay was above optimum for various life functions of the key species, and ranged from 15 °/oo to 38 °/oo (Texas Game and Fish Commission 1957; Moffett 1964; Chapman, 1966, 1972; Childress et al. 1975; U.S. Fish and Wildlife Service 1975, 1976; Hackney 1978). Salinity requirements for each of the key species were considered comparable, and a direct relationship was postulated between the effects of rediversion on oyster production and production of the other key species. Estimates of the productivity of shrimps and blue crab were made by applying the current ratio of oyster harvest to that of the shrimps and crab in Matagorda Bay. The present ratio of harvests of these species in San Antonio Bay was applied as a check; because San Antonio Bay had a freshwater inflow pattern comparable to that which could be expected in Matagorda Bay with rediversion of the Colorado River. To strengthen consistency and accuracy, only complete harvest data, published between 1962 and 1976 (U.S. Department of Commerce 1962-1976), were used in calculating the ratios in Table 2.

Two alternatives to present conditions were analyzed; i.e., full diversion of the Colorado River into West Matagorda Bay with closure of Tiger Island Cut, and construction of the navigation feature only. Potential oyster production with full rediversion of the Colorado River was estimated to be 66 percent of full historical production. This was because formation of the delta inundated an estimated 16 percent of the potential acreage for oyster reefs in the eastern arm of the bay. An additional 20 percent of the present primary oyster production was predicted to be inundated within the 50-year life of the Mouth of Colorado River Project (U.S. Corps of Engineers 1977a), and Colorado River freshwater flows had been reduced by at least 16 percent since 1931. Hydrological data for the project area (Diener 1975; U.S. Corps of Engineers 1977a; 1977b; Texas Department of Water Resources 1978c), indicated re-establishment of full Colorado River flows to the bay would result in 62 percent increase in freshwater flows reaching the bay. Construction of only the navigation feature would cause a 3 percent reduction of present gauged river discharges to the estuary (50% reduction in Colorado River inflows).

A direct relationship was assumed between changes in freshwater inflow and oyster production. Further adjustments were made for the Texas oyster cropping multiplier of 1.5 (B. D. King pers. comm.) and an estimated harvest efficiency of 35 percent (R. Hoffstetter pers. comm.).

With the above considerations, the estimated annual harvest of oysters from West Matagorda Bay with full rediversion of Colorado River flows was 786,000 kg (1,731,000 lb). Annual harvests of the other shellfish considered was 4,848,000 kg (10,714,000 lb). The value of all the species was estimated to be \$14.2 million (Matagorda Bay ratio), dockside, without applying the economic multiplier of 3.08.

GULF OF MEXICO FISHERY

The National Marine Fisheries Service (1979) estimated 11 percent of the brown shrimp and 16 percent of the white shrimp caught off the Texas Coast are produced in Matagorda Bay. Increases in gulf shrimp production attributable to rediversion is estimated to be 500,000 kg (1,102,000 lb) valued at \$2.9 million. The total annual increase in the shellfish, therefore, is estimated to be 5,348,000 kg (11,780,000 lb) worth \$17.1 million to Texas' economy (without the economic multiplier).

SUBSEQUENT ACTION

In light of the above information, conservation groups were insistent on construction of the diversion feature prior to, or concurrently with, the navigation feature. On October 24, 1978, the Galveston District Engineer (Colonel Jon Vanden Bosch pers. comm.) indicated an unwillingness to enter into a consent decree on this and other legal matters relating to the project. Considerable pressure was brought by conservation organizations through administrative channels and by threat of litigation. A Corps memorandum by the Southwestern Division Engineer, General James Donovan (February 7, 1979), indicated concern over the adequacy of the Mouth of Colorado River Project Final Environmental Statement, due to a Federal district court ruling requiring the inclusion of State agency comments on another Federal water resources project in Texas. An agreement was reached between the Corps of Engineers and Environmental Protection Agency to postpone construction of the navigation feature until after circulation of an environmental impact statement on diversion. Colonel James Sigler, the Corps' current Galveston District Engineer, reflected the Corps' position that delay of navigation construction was necessary to avoid a court injunction (Jacobs 1979).

Congressman Wyatt has been successful in placing 100 percent Federal funding provision in H.B. 4788. The U.S. Army Corps of Engineers (1980) has produced an environmental impact statement concerning the diversion feature which claims benefits to commercial fishing of only $9.4 million annually. That benefit-cost ratio, however, is still an almost unprecedented 19.2:1.

Local interests from the community of Sargent have applied for a Section 404 Permit to construct a more permanent opening at Brown Cedar Cut for recreational development. A permanent connection to the Gulf of Mexico at Brown Cedar Cut, however, would be difficult to maintain due to littoral drift. It would provide less than optimum circulation within East Matagorda Bay. Placing an opening to the Colorado River Channel at the southwest end of the bay, after construction of the diversion feature, would reduce maintenance requirements and would provide a more desirable salinity gradient.

CONCLUSIONS

1. Man-caused perturbations occurring since 1929 have greatly reduced production of economically important shellfish in Matagorda Bay, Texas.

2. Rediversion of the Colorado River to West Matagorda Bay will result in upward of $17.1 million annual benefits in shellfish landings.

3. Sedimentation in West Matagorda Bay due to diversion will have beneficial effects in reducing the open water-to-marsh ratio for the estuary.

4. The diversion feature of the Mouth of Colorado River Project should be built prior to or concurrently with the navigation feature.

5. Threat of litigation and prodding of Federal agencies by private organizations played a highly significant role in reviving the diversion feature of the Mouth of Colorado River Project.

6. After completion of the Mouth of Colorado River Project, an opening should be constructed between the south end of East Matagorda Bay and the Colorado River Channel near its mouth to facilitate exchange of marine organisms and aid in water circulation.

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CHAPTER 12

FRESHWATER INFLOW PLANNING: PART I

OVERVIEW OF FRESHWATER INFLOW DEPLETIONS

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ABSTRACT

An analysis of the accumulated depletion of streamflow in the nation's major watersheds was attempted for the first time as part of the Second National Water Assessment conducted by the U. S. Water Resources Council. This paper utilizes that data base to demonstrate the relative reduction of freshwater inflow to estuaries due to upstream water resource development. Data for normal (average) and dry (80% exceedance) year conditions is presented for 106 assessment subregions, including 30 coastal estuarine complexes. A look at the future of these complexes, given the assumptions inherent in the Council's Modified Central Case projections, is provided. The need for estuarine ecosystem-based criteria to interpret freshwater inflow depletion data is stressed.

INTRODUCTION

"Instream flow requirements.... refer to that amount of water flowing through a natural stream course needed to sustain instream values at an acceptable level. Instream values relate to uses made of water in the stream channel. They include fish and wildlife population maintenance, outdoor recreation activities, navigation, hydropower generation, waste assimilation (sometimes termed water quality, conveyance to downstream points of diversion, and ecosystem maintenance which includes freshwater recruitment to the estuaries, and maintenance of riparian vegetation and floorplain wetlands." (Bayha 1978).

While included among the family of instream uses, most instream flow studies to date have not included estuarine inflow. Likewise, most river basin development projects have not traced the effects through the receiving estuaries. Recognition of these facts was prominent in the initiation of this symposium.

The purpose of this paper is to provide an overview of man's depletion of freshwater streamflow reaching the nation's estuaries.

METHODS

Utilizing the data base assembled by the U. S. Water Assessment (U.S. Water Resources Council, 1978), I propose to illustrate, in at least two dimensions, the gross impact of man's collective water resource utilization.

This assessment was conducted by dividing the nation into 106 assessment subregions (ASR). Thirty-one of these ASRs empty directly into estuarine systems of the conterminous 48 states (Figure 1).

For each of these ASRs an analysis was made of the depletion of the water supply from three perspectives:

- -1975 level of development with ground water mining.
- -1975 level of development without ground water mining.
- -Before water resource development

The following descriptions were taken from Bayha (1978).

CURRENT STREAMFLOW DEPLETION RATIO

The current streamflow depletion ratio is an expression of the depletion of total water supply today.

$$\begin{array}{l}\text{Current}\\ \text{Streamflow}\\ \text{Depletion}\end{array} = \frac{\begin{array}{l}\text{"1975"}\\ \text{Consumptive}\\ \text{Requirement}\end{array}}{\begin{array}{l}\text{Current}\\ \text{Streamflow}\\ \text{Supply}\end{array}}$$

Current Streamflow Supply is that flow expected to exist if all consumption were eliminated and "1975" management practice and groundwater overdraft were continued at "1975" levels. "1975" was the base year for the Second National Water Assessment data; it represents assumed average conditions and quotation marks are used throughout this text to indicate that the 1975 data are not actual data.

$$\begin{array}{l}\text{Current}\\ \text{Streamflow}\end{array} = \begin{array}{l}\text{Current}\\ \text{Consumptive}\\ \text{Supply}\end{array} + 1975$$

Current streamflow is historically derived streamflow for "1975" and includes contributions from ground water overdraft.

This ratio assumes that current net exports, net evaporation and groundwater overdraft (mining) are reflected in the current streamflow supply. These ratios were computed only for "1975" and are found in "U. S. Water Resources Council 1978, Volume 3, Table II-5, Column 21".

ASSESSED STREAMFLOW DEPLETION RATIO

The assessed streamflow depletion ratio is similar to the current streamflow depletion ratio. It is an expression of the depletion of today's surface water supply under the most likely future conditions (i.e., consumption as projected by the Federal agencies, an assumption that groundwater mining in the future will cease, and, in certain basins, the assumptions that there will be some increase in reservoir evaporation as new storage is developed and that there will be some change in net exports).

Chart 1

$$\begin{array}{l}\text{Assessed}\\ \text{Streamflow}\\ \text{Depletion}\\ \text{Ratio}\end{array} = \frac{\text{Offstream Use}}{\text{Assessed Total Streamflow}} \quad \text{or}$$

$$\frac{\begin{array}{l}\text{Consumptive}\\ \text{Requirement}\end{array} + \begin{array}{l}\text{Change in}\\ \text{Evaporation}\end{array} + \begin{array}{l}\text{Change in}\\ \text{Net Export}\end{array}}{\begin{array}{l}\text{Current}\\ \text{Streamflow}\end{array} + \begin{array}{l}\text{"1975" Consumptive}\\ \text{Requirement}\end{array} - \begin{array}{l}\text{Ground Water}\\ \text{Overdraft}\end{array}}$$

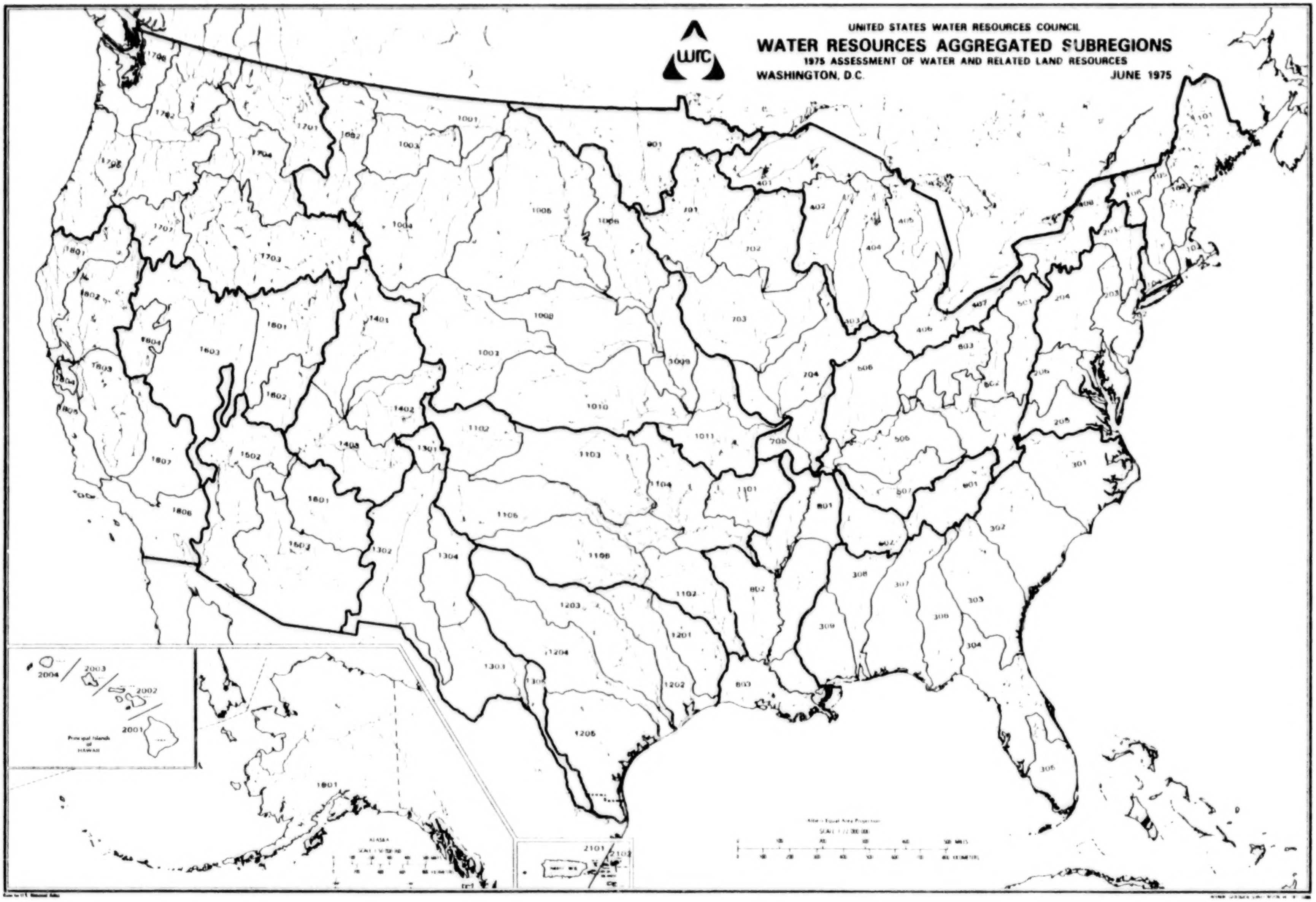

Figure 1. Water resources aggregated subregions.

Assessed Total Streamflow is the theoretical quantity of streamflow that would be available if all projected additional consumption were eliminated and "1975" management practices (reservoir management and water transfers) were continued. Contributions from groundwater overdraft are excluded in determining assessed total streamflow.

These ratios were computed for "1975", 1985, and 2000 and are found in: U.S. Water Resources Council 1978, Volume 3, Table II-5, Column 22.

The natural streamflow depletion ratio expresses the impact of offstream uses on historical instream flow conditions. That is, the point of perspective predates development of water resources. The denominator approximates the natural flow before development (including interactive aquifiers contributions) as closely as the data permit. Thus, analysis of the depletion of natural flow provides a truer indication of the relative current and projected instream flow conditions than either the current or assessed streamflow depletion ratios described above. See Chart 1.

Natural outflow is the estimated streamflow in the so-called natural state, i.e., before human influence. Natural outflow is similar to total streamflow in eliminating consumption and groundwater overdraft. In addition, all water transfer and evaporation from man-made reservoirs is eliminated. This is not a true natural streamflow because the vegetation and runoff patterns have been altered to meet human needs. Natural water supply analysis results can be found in U.S. Water Resources Council 1978, Volume 3, Table II-6.

Natural Outflow =
Assessed Total Streamflow +
Reservoir Evaporation +
Exports -
Imports

Unfortunately, this ratio (found in U. S. Water Resources Council 1978 Volume 3, Table II-6, Column 17) can only be computed for average annual considerations due to the limitations in our data with respect to the influence of storage. Comparisons of Natural Streamflow Depletion Ratios with Assessed Streamflow Depletion Ratios reveal the significance of viewing the relative severity of streamflow depletion from two temporal perspectives.

These ratios permit all subregions to be equitably compared despite their varied histories with respect to depletion, transbasin diversion, and groundwater overdraft.

Tennant (1976) provided descriptions of streamflow conditions useful as criteria to evaluate the relative impact of changes in instream flow conditions (as indicated by depletion ratios) in freshwater stream ecosystems. By subtracting Tennant's percentage criteria (which relate to the conditions in the stream channel) from unity, we have an expression of the complementary depletion level (description of the offstream use). Thus,

60% mean annual flow =
40% depletion of surrogate flow
30% mean annual flow =
70% depletion of surrogate flow
10% mean annual flow =
90% depletion of surrogate flow

Surrogate flows are "Current Streamflow Supply", "Assessed Total Streamflow", and "Natural Outflow", as outlined in Bayha (1978). The following descriptions can be used in discussing the relative instream flow conditions.

Severe - depletion equal to or greater than 90%
Stressed - depletion from 70% to 90%
Degraded - depletion from 40% to 70%

However, for interpreting the impact on estuarine ecosystems there is no equivalent criteria. Therefore, the results are presented as depletion ratio data, leaving the interpretation for later analysis when suitable criteria are available.

RESULTS

The following series of figures presents the relative depletion for all ASRs over an average year of current streamflow supply (Figure 2), assessed total streamflow (Figure 3), and natural outflow (Figure 4). Analysis of these data reveals the relative importance of the different assumption embodied in the three types of depletion ratios. Notably, only in Texas is the assumption involving ground water mining significantly influencing the amount of depletion of freshwater inflow to estuaries (Figures 2 and 3). Figure 4 shows that natural flow depletion is somewhat higher than comparable assessed streamflow depletion (Figure 3).

Figures 5 and 6 present comparable data for dry year conditions to those in Figures 2 and 3. The higher depletion ratios are a function of both lower surface water supplies and higher water use, particularly by irrigated agriculture. Obviously, the stress on estuarine ecosystems is greater but without criteria it is difficult to interpret the implication of this stress.

Figures 7, 8, and 9 present projected depletion ratios for the year 2000 based on the most likely future as determined by the Federal agencies participating in the assessment. Comparing these data with those in the previous series such as the "1975" series (Figures 3, 4, and 6) reveals the relative magnitude of anticipated further depletion of freshwater inflow to the estuarine complexes. As expected, the direction of change is toward greater depletion except along the Texas coast. Here, reduced depletion ratios are shown. Because of declining water tables and the corresponding increase in pumping costs, it was assumed that groundwater overdraft will be reduced in the future, particularly in the agricultural sector.

These annual depletion ratios illustrate the magnitude of the combined efforts of man's development of upstream water supplies. A more incisive picture is available through examination of monthly depletion ratios.

However, the monthly depletion data are too voluminous to present here. But I will utilize the data for ASR 803 (Mississippi Delta-Louisiana Coast) as an illustration of the monthly analysis potential which the assessment data offer (Table 1). Such data are available for all ASR for both average and dry year conditions.

CONCLUSIONS AND RECOMMENDATIONS

It is clear from the Second National Assessment data that (1)

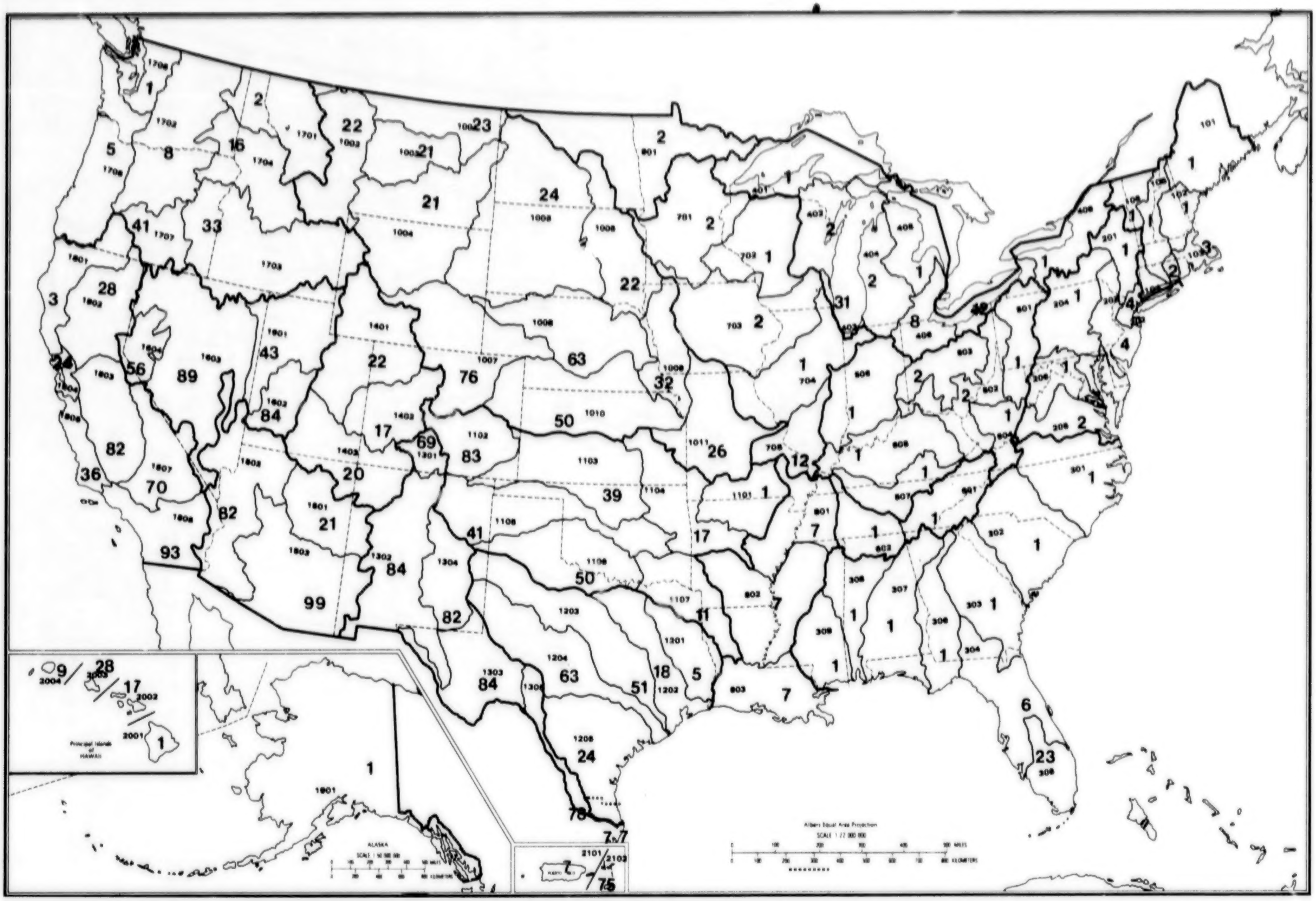

Figure 2. Current streamflow depletion ration (%) for average year conditions--"1975" (from Columns 21 Table II-5, Appendix II, Volume 3, Second National Water Assessment).

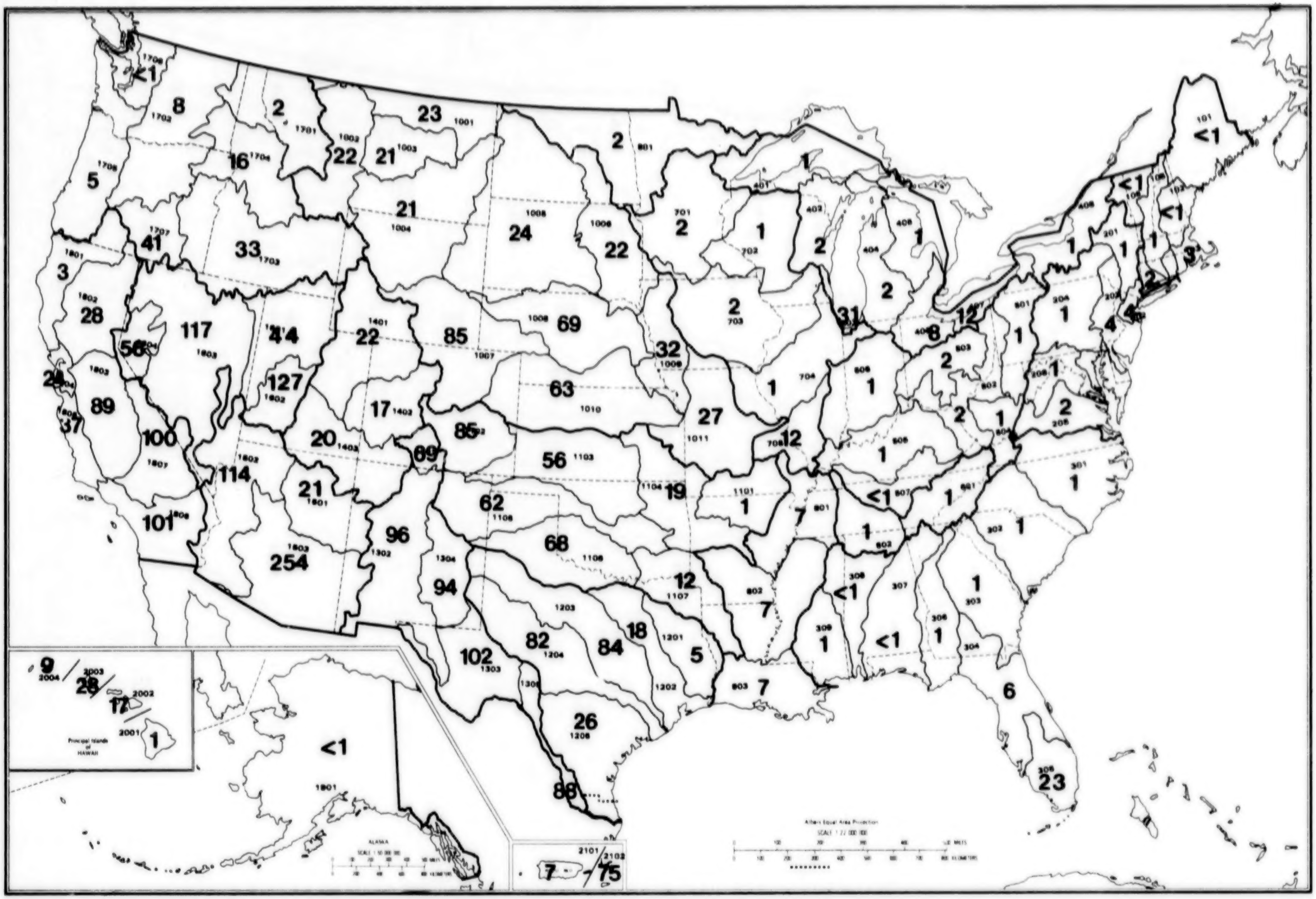

Figure 3. Assessed "1975" streamflow depletion ration (%)--average year--indicating relative instream flow conditions (From Column 22, Table II-5, Appendix II, Volume 3, Second National Water Assessment).

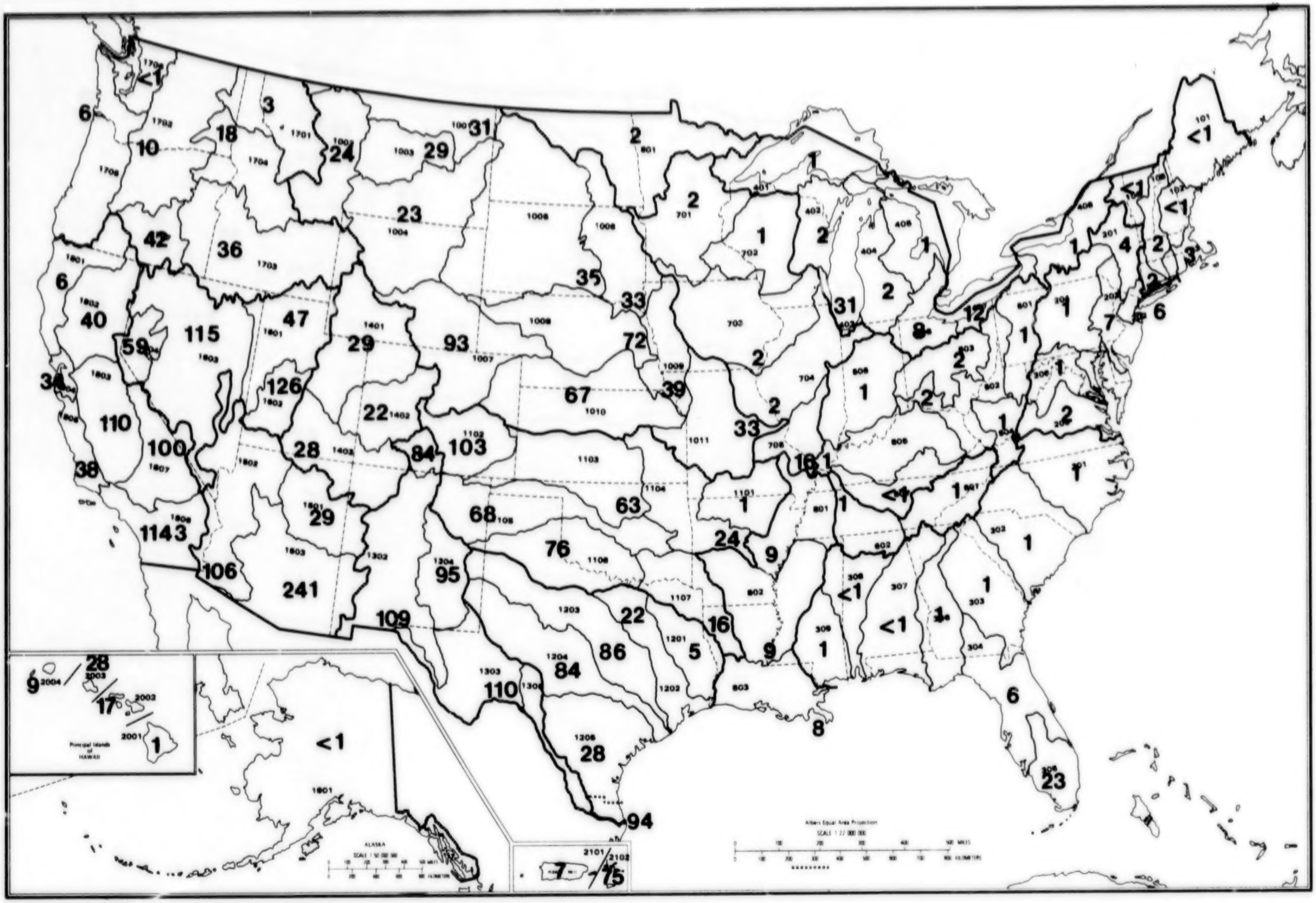

Figure 4. "1975" natural flow depletion ration (%)--average year--annual (from Column 19, Table II-6, Appendix II, Volume 3, Second National Water Assessment).

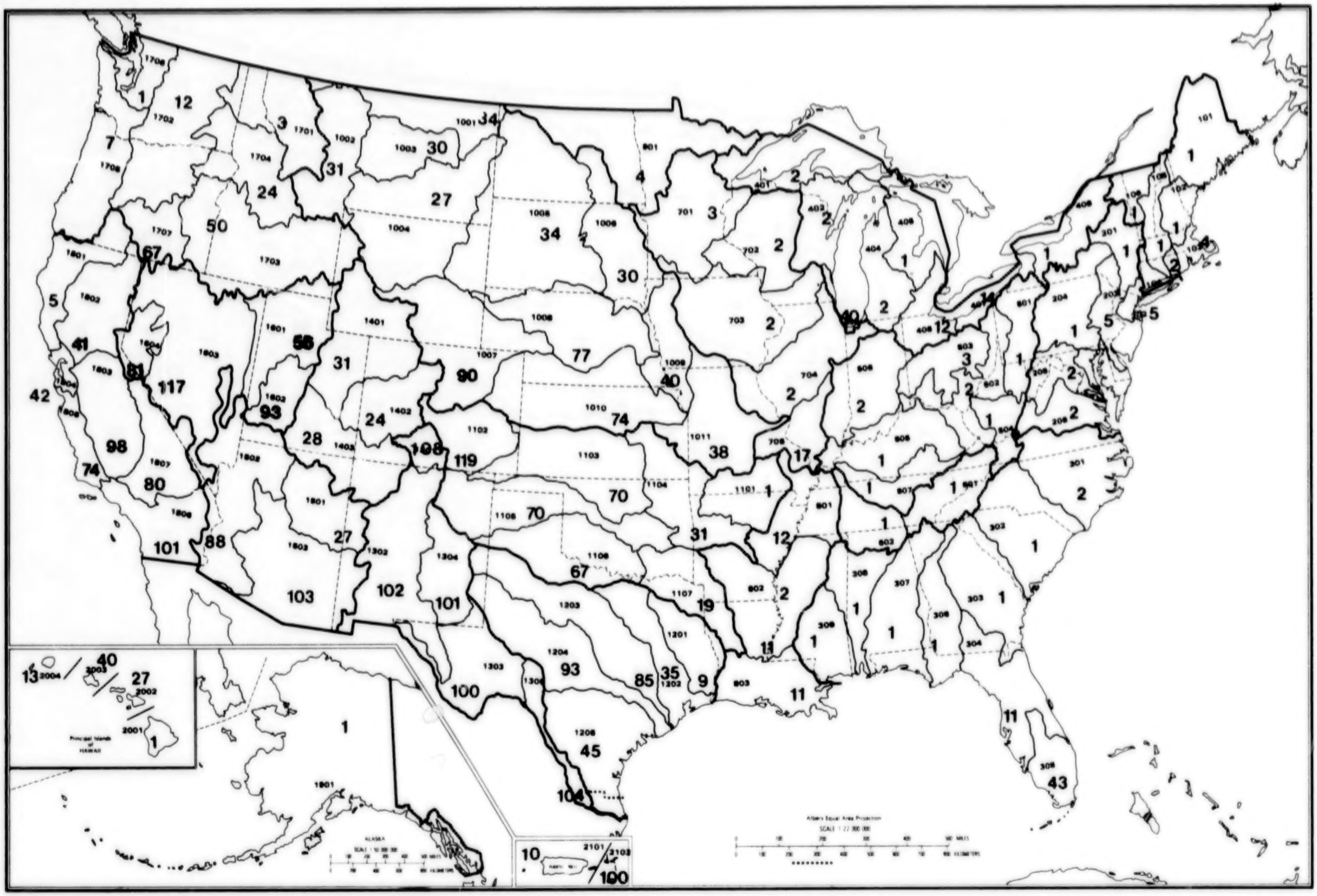

Figure 5. Current streamflow depletion ratio (%) and for dry year conditions--"1975" (from Column 21, Table IV-2, Appendix IV, Volume 3, Second National Water Assessment).

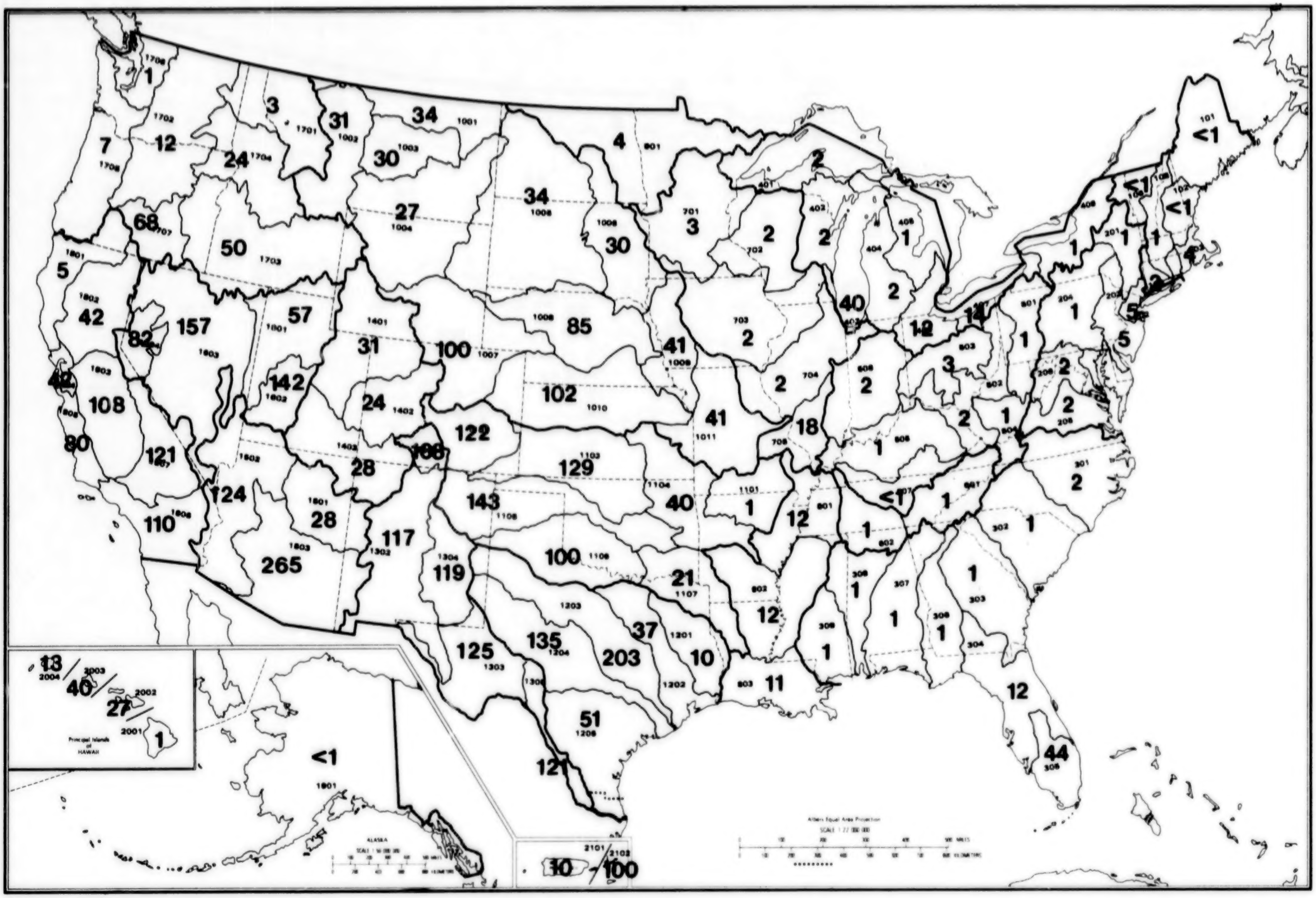

Figure 6. Assessed "1975" streamflow depletion ratio (%)--dry year--indicating relative instream flow conditions (from Column 22, Table IV-2, Appendix IV, Volume 3, Second National Water Assessment).

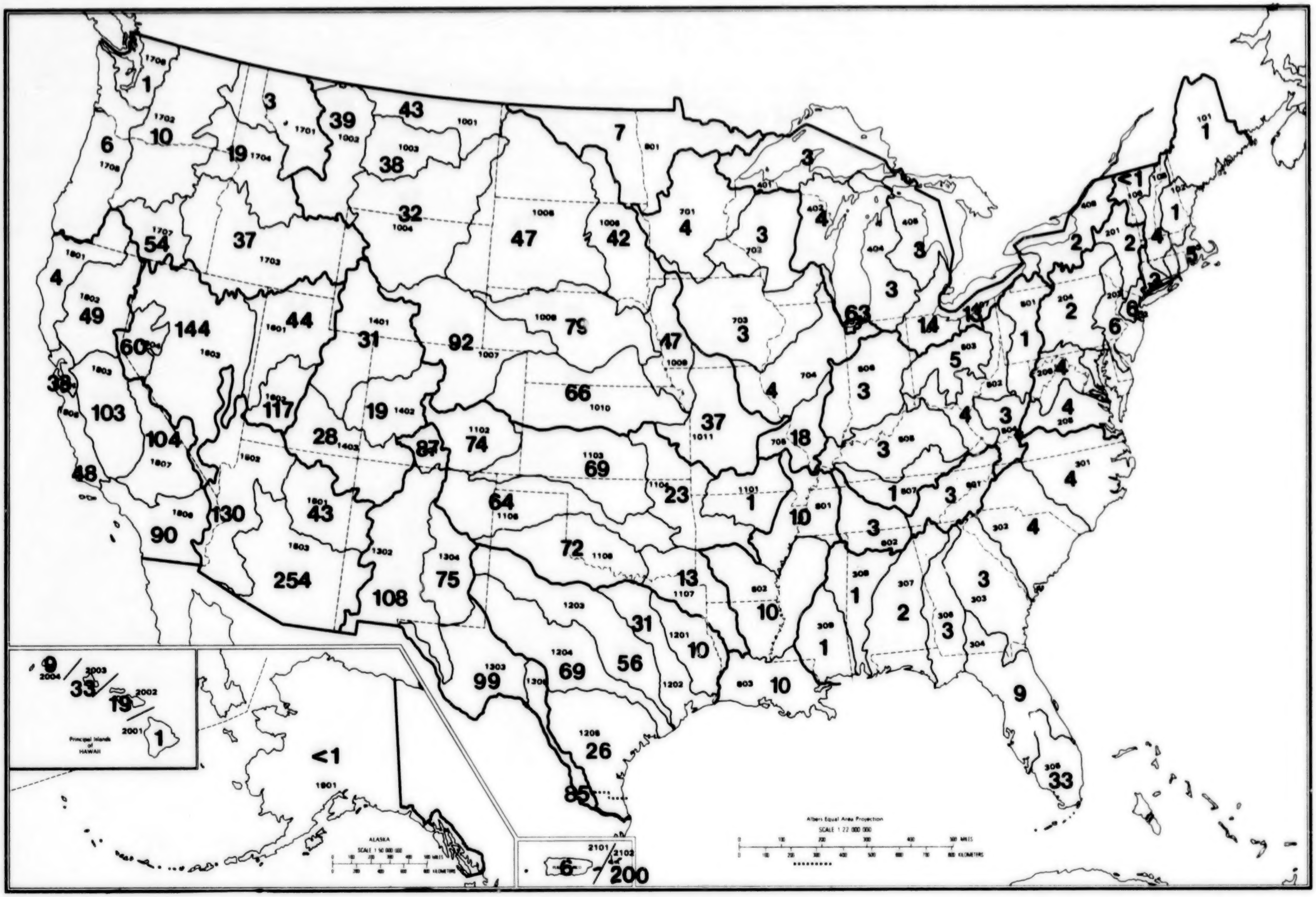

Figure 7. Assessed 2000 streamflow depletion ratio (%)--average year--indicating relative instream flow conditions (From Column 22, Table II-5, Appendix II, Volume 3, Second National Water Assessment).

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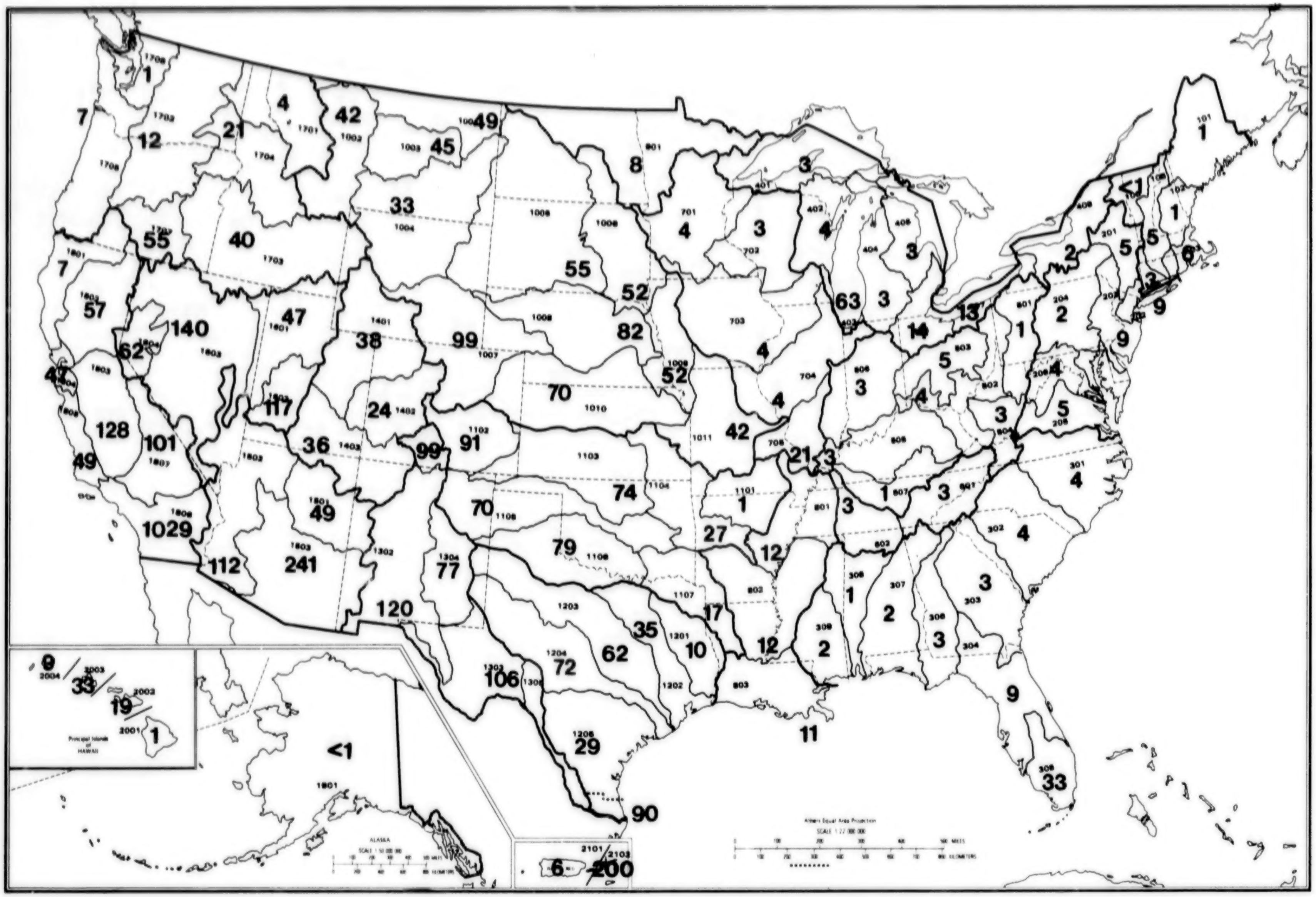

Figure 8. 2000 natural flow depletion ratio (%)--Average year--annual (from Column 19, Table II-6, Appendix II, Volume 3, Second National Water Assessment).

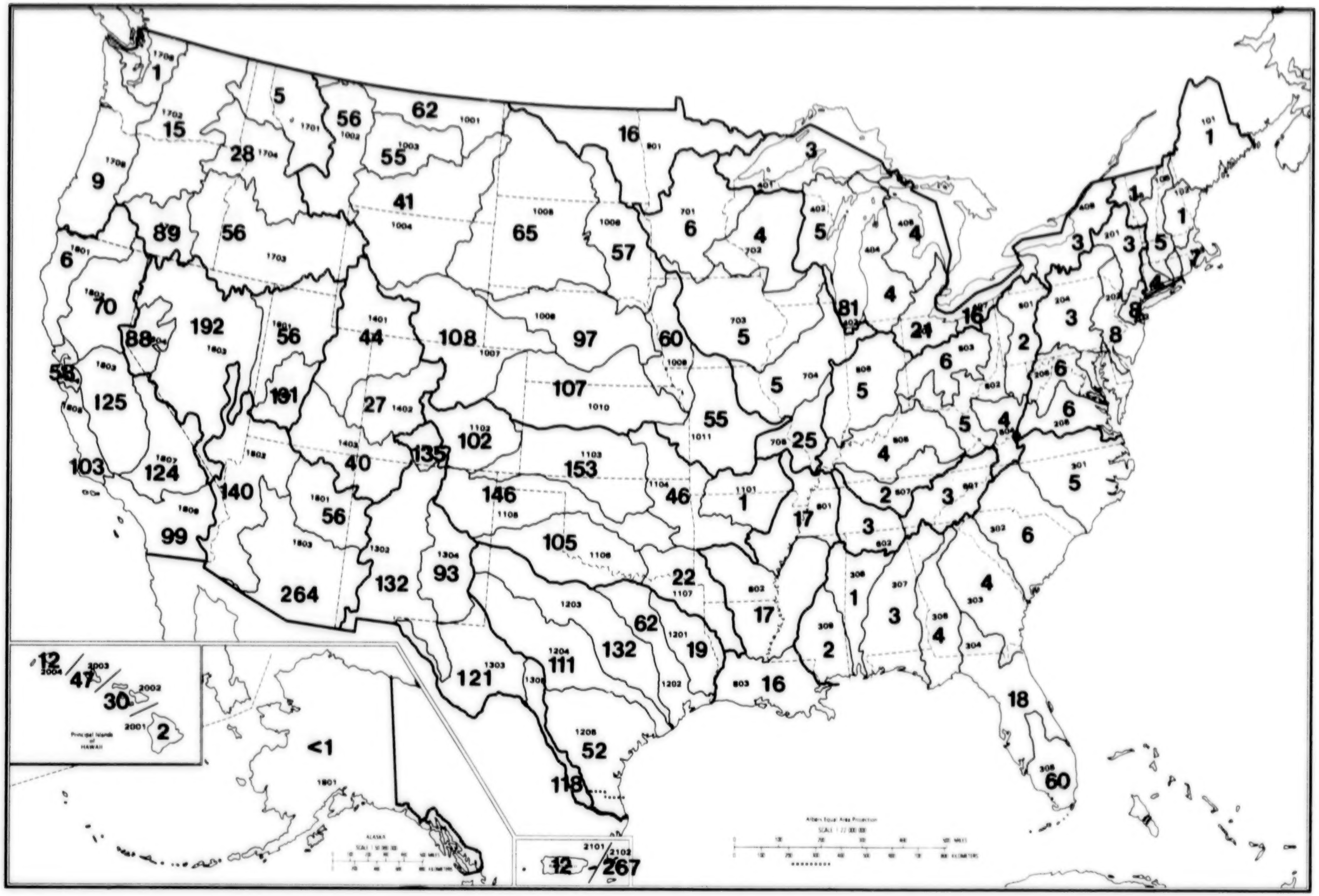

Figure 9. Assessed 2000 streamflow depletion ratio (%)--dry year--indicating relative instream flow conditions (from Column 22, Table IV-2, Appendix IV, Volume 3, Second National Water Assessment).

Table 1.

SECOND NATIONAL WATER ASSESSMENT
JANUARY 1978 (DRAFT)

MONTHLY STREAMFLOW DEPLETION ANALYSIS
*** DRY YEAR ***

MISSISSIPPI DELTA
LOWER MISSISSIPPI

	(1) CURRENT STRMFLW AT OUTFLW PT (MGD)	(2)* FUTURE STRMFLW AT OUTFLW PT (MGD)	(3) CONSUMPTION REQ.	(4)	(5)** CHANGE IN NET EXPORTS ABV OP (MGD)	(6) CHANGE IN NET EVAPOR ABV OP (MGD)	(7) GROUND WATER WTHDRAW IN UNIT (MGD)	(8) GROUND WATER MINING	(9)	(10) TOTAL STRMFLW (1+***5 +6-9) (MGD)	(11) CURRENT STRMFLW DEPLETION (4+***6)/ (1+***5+6)	(12)* FUTURE STRMFLW DEPLETION (4+***6) /(2)
			IN HYDRO UNIT (MGD)	ABOVE OUTFLW PT (MGD)				IN HYDRO UNIT (MGD)	ABOVE OUTFLW PT (MGD)			
...1975...												
JANUARY	244000	242909	608	5185	0	0	542	67	1100	248994	2%	2%
FEBRUARY	334000	332666	604	6595		0	542	67	1334	339141	2%	2%
MARCH	452000	449928	635	8424	0	0	542	67	2072	458030	2%	2%
APRIL	509000	505224	2562	13345	0	0	1589	198	3776	517590	3%	3%
MAY	484000	477580	4641	27804	0	0	2733	340	6420	503726	5%	6%
JUNE	324000	312418	6213	63244	0	0	3582	446	11582	368965	16%	17%
JULY	254000	225476	2978	11[illegible]195	0	0	1776	221	28524	327831	30%	34%
AUGUST	181000	152497	1560	102796	0	0	981	122	28503	242171	36%	42%
SEPTEMBER	146000	134326	668	46[illegible]76	0	0	542	67	11674	171311	24%	27%
OCTOBER	128000	124408	660	14230	0	0	542	67	3592	136456	10%	10%
NOVEMBER	139000	137509	655	014	0	0	342	67	1491	144280	5%	5%
DECEMBER	185000	183955	639	6164	0	0	542	67	1045	190047	3%	3%
ANNUAL	282000	273574	1869	34339	0	0	1294	150	8426	304379	11%	11%
...1985...												
JANUARY	-	240836	859	9227	-107	140	-	0	0	-	-	3%
FEBRUARY	-	331000	850	9151	-100	206	-	0	0	-	-	2%
MARCH	-	449266	884	9993	-265	357	-	0	0	-	-	2%
APRIL	-	504848	2437	13254	-94	561	-	0	0	-	-	3%
MAY	-	472705	4140	32268	-132	538	-	0	0	-	-	7%
JUNE	-	301246	5583	73960	-380	836	-	0	0	-	-	20%
JULY	-	195260	3115	139571	223	1617	-	0	0	-	-	47%
AUGUST	-	126411	2059	127082	197	1596	-	0	0	-	-	53%
SEPTEMBER	-	124413	929	54626	133	1230	-	0	0	-	-	33%
OCTOBER	-	122351	916	15670	-108	726	-	0	0	-	-	12%
NOVEMBER	-	135523	910	9742	-108	367	-	0	0	-	-	6%
DECEMBER	-	181704	893	8362	-107	160	-	0	0	-	-	4%
ANNUAL		265797	1965	41492	-71	695	-	0	0	-	-	14%
...2000...												
JANUARY	-	235984	1450	13365	-496	236	-	0	0	-	-	5%
FEBRUARY	-	326262	1431	13136	-489	347	-	0	0	-	-	4%
MARCH	-	444467	1468	13939	-654	606	-	0	0	-	-	3%
APRIL	-	500123	2825	17981	-479	945	-	0	0	-	-	4%
MAY	-	468171	4335	35707	601	905	-	0	0	-	-	7%
JUNE	-	296545	5710	76967	744	1406	-	0	0	-	-	21%
JULY	-	180172	3642	149567	3211	2721	-	0	0	-	-	47%
AUGUST	-	114608	2760	133139	2855	2684	-	0	0	-	-	58%
SEPTEMBER	-	119806	1533	56625	1909	2069	-	0	0	-	-	35%
OCTOBER	-	117966	1510	19945	-495	1222	-	0	0	-	-	16%
NOVEMBER	-	130664	1504	17717	-496	618	-	0	0	-	-	10%
DECEMBER	-	176653	1486	13692	-496	270	-	0	0	-	-	7%
ANNUAL	-	259618	2471	45650	476	1169	-	0	0	-	-	16%

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* (2),(12) FUTURE STREAMFLOW BASED ON CESSATION OF GROUND WATER MINING.
** (5),(11),(12) COLUMN (5) IS NEGATIVE WHEN THERE IS AN INCREASE IN IMPORTS OR A DECREASE IN EXPORTS.
ONLY POSITIVE VALUES OF (5) ARE CONSIDERED DEPLETIONS IN COMPUTING (11) AND (12).

*** (10),(11),(12) TOTAL STREAMFLOW USES 1975 AVERAGE CONSUMPTION (4) FROM TABLE 32A.

man, through his water resource development activities, has markedly impacted the freshwater inflows to some of the Nation's estuaries, (2) that projected growth based on trend planning and resulting future developments would produce additional impacts, and (3) that the nature of these impacts involve the quantity and timing of the freshwater inflow.

Without suitable criteria for evaluating the effect of these changes on the well being of the estuarine ecosystems, it will be difficult to receive fair consideration in future decisions regarding water allocation and development. With such criteria, water resource planners could link estuarine needs for freshwater inflow with instream flow needs to permit meaningful evaluation of impacts of water projects proposed for development in the headwaters. The ability to track effects of a change downstream to and through the estuary would help the coastal community to assure inclusion of estuarine values in the tradeoff analysis made by upriver planners and presumably the continued production of our most valuable ecosystems.

I recommend that investigators working in the estuaries who have data which might provide the basis for the needed criteria should contact the Cooperative Instream Flow Service Group. And further that this symposium recommend that the water planning community adopt a carrying capacity approach to planning and that they track the effects of proposed development through the estuary.

AUTHOR'S NOTE

Rozengurt and Haycock's paper presented in these proceedings offers insight which can provide the needed criteria for interpreting the implications of depleted freshwater inflows. They state, "Direct experience (in Russia and elsewhere) and the published results of the effects of water development abroad all point to the inescapable conclusion that no more than 25 percent of the natural outflow can be diverted without disastrous ecological consequences ensuing." These authors further recommended that 50 percent depletion be recognized as the absolute limit on further development.

This information squares well with the results presented herein and the known conditions of our estuarine ecosystems. Therefore, I suggest that (1) the U.S. Environmental Protection Agency give serious consideration to promulgating a standard for cessation of further consumptive depletion of natural freshwater inflow until it can be shown that additional depletion can be tolerated, and (2) that the U.S. Water Resources Council include as part of the President's proposed Independent Project Review Process a criterion for evaluating adherence to such a standard.

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DISCUSSION

Question: Tommy Yokum, National Marine Fishery Service, Tiburon California: I was close enough to read your figures and being intimately associated with the San Francisco Bay Estuary, had real problems with them and it makes me wonder what some of the data are that you have available. In your projection of the year 2000, for a dry year you indicated the estuary would have about a 59 percent reduction or depletion. In the recent drought the depletion was 90 percent. For a normal year you showed the estuary having about 34 percent depletion, and at present it's approaching 70 percent. And to the extent that these data are used by national planners, I hope that maybe we can get some better information?

Answer: In response to your question, I can only tell you that these data are in the national assessment. I can tell you a little bit about where they came from. The stream flow supply data, that is how much is in the current stream flow, was computed by the U.S. Geological Survey. The projection for irrigated agriculture, and that's the dominant driving force there in California, was put together by a model developed in Ames, Iowa, called the heavy model, done for the U.S. Department of Agriculture. They got their figures on how much water is consumptively used in this manner. There are so many acres that are growing crops and consuming so much water. And through a multiplying process they come out with this much used by the agriculture sector. The Bureau of Reclamation in California took issue with the Department of Agriculture's numbers. The State of California took issue with those numbers. And there is in the National Water assessment the California version of the data. And this is one of the places in the Nation where the most likely future is described by the Federal water planning community in Washington D.C. And I say that in Agriculture they use this model. What the regional water planning people believe differ. So if you want to consult the nuts and bolts of how these numbers came to be there is a difference in California between the "official" set of data, and the California picture. I might also comment that the feds say the folks of California are skewing their numbers in the other direction on purpose. I'm not quite sure what the reason for that is, but the charge has been said verbally.

Comment: Keith Bayha U.S. Fish and Wildlife Service, Fort Collins, CO: Mr. Yokum asked me a good question, and I have to apologize. It's been a couple of years since I really studied these data very much. I made an error. I should have painted in purple the Sacramento- San Joaquin Basin because the Water Resource Council did an interesting thing. They treated the inflow of the Sacramento and the San Joaquin into the delta as dumping into the sea. So the numbers--47 at this particular slide--is past the Sacramento Bay area and really represents the surface water run off supply of that small area right around the bay and the use by the people in that bay. You see the San Joaquin Basin is 128 percent depleted that's only possible because they're ripping off a big chunk of the Sacramento. The Sacramento depletion is 57 percent. What that means is the consumption in the Sacramento Basin itself is 57 percent of the supply of the Sacramento Basin. The transbasin diversion to the San Joaquin is put back in the Sacramento and that's the supply, and it's 57 percent depleted by the Sacramento and the people that live in the Sacramento Basin. So to get what you are looking at, you need to compare these other numbers to the dimension. You take those three basins and work them together in a different formula.

MANAGEMENT, PLANNING, AND ORGANIZATION IN INITIATING, SUPPORTING AND COORDINATING AN ONGOING FRESHWATER DIVERSION PROJECT

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ABSTRACT

The objective of this paper is to review the management, planning, and organization that have been utilized in the development of an ongoing project relative to freshwater inflows into the western Mississippi and eastern Louisiana estuaries. The name of the project is "Mississippi & Louisiana Estuarine Areas" (Hydrologic Unit I and Mississippi Sound). In August 1973, a group of seafood industry people requested the Mississippi Sea Grant Program and the University of Southern Mississippi to assist them in solving some of their problems. One of the problems was the decline of seafood productivity, with one of the reasons for the decline being the lack of fresh water on a controlled basis into the several marine estuaries in the Mississippi and Louisiana areas. A task force was set up, which included both industry persons and marine biologists (state, Federal and university). This paper describes the methodology used in initiating and continuing a cooperative venture of a large project which entails local, state and Federal cooperation of commercial and recreational fishery interests at all levels. Currently, the U.S. Army Corps of Engineers, New Orleans, is finalizing the Stage I report, which was initiated on October 1, 1977.

INTRODUCTION

In August 1973, a group in the seafood industry requested that the Mississippi Sea Grant Program and the University of Southern Mississippi assist them in solving some of their problems. One of the problems was the decline of seafood productivity, with one of the reasons for the decline being the lack of fresh water on a controlled basis into the several estuaries in the Mississippi and Louisiana areas. It was agreed upon by the group that this project was important enough to pursue and to seek possible ways and means of solving the problem.

Prior to the building of the levee system along the lower Mississippi River, periodic flooding replenished the estuaries with fresh water. This fresh water carries nutrient salts that are utilized by marine life as a food source and deters saltwater encroachment. The present levee system, while doing an excellent job of its intended purpose of preventing flooding, diverts the fresh water through the mouth of the Mississippi River and out into the Gulf of Mexico. This flow bypasses many of our estuaries.

Experience from fishery establishments on the Mississippi and Louisiana coasts, observations, and scientific studies indicate and support the conclusion that appropriate discharges of fresh water into estuarine areas, on a controlled basis, enhance fish and wildlife productivity. Fishery production, similar to land crops, is hindered by too much fresh water as well as the lack of it. Various projects have been undertaken to control flood waters and the adverse effects of droughts on land crops; however, very little effort has been expended to supply fresh water to our estuaries when needed.

A task force was established by the group to explore ways and means of obtaining controlled fresh water into the estuaries east of the Mississippi River via the Bonnet Carre Spillway. Task leaders established were Victor Mavar (Mavar Shrimp and Oyster Company, Biloxi) and David J. Etzold (Sea Grant Principal Investigator, University of Southern Mississippi).

It was determined that a study would need to be conducted to establish a document to be presented to Congress requesting that Congress direct the U.S. Army Corps of Engineers in New Orleans to develop ways and means of solving the problem.

METHODS

As a first step, a preliminary plan was made which attempted to anticipate both advantages and disadvantages to the proposed project. A listing was prepared of those who might be opposed to as well as those in favor of such an endeavor.

A summary of that planning session to assess the feasibility of the project included the need for the following factors to be considered and evaluated:

1. Technical--will the course of action be a viable effort that does not approach or exceed the state of the art?

2. Environmental--will the course of action change the environment in acceptable ways only, in both the short and long runs?

3. Economic--will the course of action result in a benefit-to-cost ratio of 1.0 or greater? Have all costs, including social, been considered?

4. Financial--will there be funds available to pay for implementing the course of action?

5. Social--will those involved respond to the course of action in a manner commensurate with program goals and objectives?

6. Political and Legal--can the course of action acquire and maintain the political support required for successful implementation? Does it conform to applicable laws, or must they be changed?

Before any "best" alternative can be considered totally viable, efforts must be expended to determine the consequences of such action and summarized in a manner that decision makers can use in selecting a best composite course of action for use in a specific situation for both short and long run implications. Thus, a total systems approach must be taken, which implies performing a complete effort involving much time by a number of people.

Using the above framework, some of the activities included the following

1. Determine what needs to be done and who can best do it.

2. Set up a timetable of events so that progress (or lack of it) can be measured.

3. Be flexible in plans.

4. Solicit help from existing agencies that can contribute toward understanding and success of the project.

A summary of the level of detailed efforts expended in organizing and planning the initial stages of this project is outlined in a publication by Etzold and Williams (1974). Some of the efforts included a trip to New Orleans to discuss the project with the Executive Director of the Mississippi Marine Resources Council and his staff.

Discussions ensued with the National Marine Fisheries Service at Pascagoula, Mississippi, and discussions and guidance were obtained from members of the Gulf Coast Research Laboratory at Ocean Springs, Mississippi. Several discussions and visits were made to the Army Corps of Engineers, New Orleans Planning Division, the Mississippi Director of the Office of Science and Technology in Jackson, and the NASA Earth Resources Laboratory at Mississippi Test Facility in Bay St. Louis.

A presentation to the National Sea Grant site team in November 1973, at Biloxi, Mississippi, included this project, which was funded. Articles appeared in the Mississippi gulf coast newspapers a number of times and the project was discussed on WLOX-TV. The project was discussed with the Mayor and City Commissioner of Biloxi, Mississippi. The Coastal Zone Management meeting at Baton Rouge was attended in February 1974, to discuss the project with Louisiana attendees.

A formal presentation was made to the Gulf States Marine Fisheries Commission Technical Coordinating Committee in New Orleans on March 20, 1974, to gain support for utilizing the Bonnet Carre Spillway as a freshwater source. In effect, the Technical Coordinating Committee would not endorse the project without a feasibility study being conducted first.

A meeting was held next in Vicksburg on April 10, 1974, with Major General Charles Noble, President of the Mississippi River Commission and Division Chief, U.S. Army Corps of Engineers, and members of his staff. General Noble expressed interest in the project and stated that he felt the best route to pursue would be a general feasibility study to determine all alternative potential sources for supplying supplemental fresh water on a controlled basis to enhance seafood productivity, sports fishing and other wildlife activities in the estuarine areas. Upon our requests, General Noble assigned members of his staff to help in formulating a resolution for presentation to the appropriate legislative delegations for consideration and action.

As a result of comments from the Gulf States Marine Fisheries Commission Technical Coordinating Committee and General Noble, the approach was altered somewhat. Instead of focusing on utilizing the Bonnet Carre Spillway as the freshwater source, the plan was modified to request a general feasibility study to encourage all alternative source possibilities of freshwater diversion into the necessary estuaries.

The next step was to review a copy of House Document 308-88/2 (under the title of Mississippi River and Tributaries Project, U.S. Army

Corps of Engineers 1964). This study supported the introduction of fresh water into estuaries to improve seafood productivity However, it could not be determined who should supply the necessary funds. Since that time, there has been a change in policy. Several other studies were reviewed for background information.

The resolution written on our behalf by the Vicksburg Division of the U.S. Army Corps of Engineers is reproduced in full:

"Resolved by the Committee on Public Works of the U.S. Senate (and House) that the Chief of Engineers of the U.S. Army be, and is hereby requested to review the report on the Mississippi River and tributaries, published as House Document 308, 88th Congress, and other pertinent reports, with a view to determining the advisability of modifying the recommendations contained therein with particular reference to providing freshwater into Lake Maurepas, Pontchartrain, Borgne, and Mississippi Sound areas in the interest of improving the wildlife and fisheries resources of this area."

With the receipt of this resolution, the next planning efforts entailed the solicitation of widespread support of the project. The following endorsements were obtained during the next twelve months:

Mississippi Marine Conservation Commission	May 1974
Lousiaina Oyster Dealers & Growers Association	August 1974
American Shrimp Canners Association	September 1974
Mississippi Marine Resources Council	September 1974
Gulf States Marine Fisheries Commission	October 1974
New Orleans Sportsmen's League Directors	November 1974
Gulf Coast Research Laboratory	February 1975
Louisiana Wildlife Federation, Inc.	March 1975
Louisiana Outdoor Writers Association	March 1975
Louisiana Wildlife Biologists Association	March 1975
Louisiana Wildlife & Fisheries Commission	March 1975
Mississippi Game & Fish Commission	April 1975

With the above endorsements supporting the project, it was determined that sufficient support on a broad basis had been established, and the next step was taken. A document was put together for presentation to the U.S. Army Corps of Engineers and appropriate numbers of Congress (House and Senate). The unpublished document was an industry request for the U.S. Army Corps of Engineers to conduct a feasibility study with a view of determining potential sources of fresh water to Mississippi and Louisiana estuaries and their controlled diversion to these estuaries to enhance fish and wildlife production.

The contents of this document included:

I. Conclusions and Purpose

II. List of Previous Endorsements

III. Resolution Draft Written by the U.S. Army Corps of Engineers

IV. Appendices

  A. Resolutions

  B. Participants to Contract

  C. Extracts From Previous Studies.

Through efforts of many, a meeting was set up on March 4, 1976, in the Forrestal Building, Washington, D.C., for presenting our request to the Chief of the U.S. Army Corps of Engineers, Lieutenant General William C. Gribble, members of his staff, and the Mississippi, Louisiana, Alabama, and Texas representations in Congress. Our task force included nine people, with marine fisheries biology personnel from Mississippi, Louisiana, and Alabama as well as seafood industry personnel. It is felt that the strong showing of interest plus a well-researched and documented plan greatly enhanced acceptance of our request.

The agenda presentation was as follows:

I. Introductory Comments

II. Brief History of Committee Actions

III. Overview of Supporting Documents

V. Questions and Discussion

We were commended for our depth of preparation during the past two years and the documentation submitted for review and consideration. The outgrowth of the presentation was that Lieutenant General Gribble and his staff reviewed the resolution to insure adequacy of its contents. The draft was then turned over to the appropriate members of Congress to be submitted to the Committee on Public Works of the U.S. Senate and House of Representatives. Our task force agreed to assist both the U.S. Army Corps of Engineers and our Congressional delegations in whatever manner necessary to enhance early initiation of the study.

The study, entitled the "Mississippi and Louisiana Estuarine Areas," was authorized by a resolution adopted September 23, 1976, by the House of Representatives at the request of Congressman Trent Lott of Mississippi. Thus, with the prime responsibility of the project shifted to the New Orleans District, U.S. Army Corps of Engineers, the first phase of the task (which encompassed a time frame of some three years) was completed. The major thrust of the task force remains one of monitoring and support, as may be required.

Continuing efforts have been keeping interested parties informed as to the status of the project. Periodic reports have continued to be made at the annual American Shrimp Canners Association conferences, as well as the semiannual Gulf States Marine Fisheries Commission conferences. In addition, support to the U.S. Congress remains an annual event, especially at budget input and hearings times. Review with the U.S. Army Corps of Engineers, New Orleans District, remains on an "as required" basis.

As of August 1979, the U.S. Army Army Corps of Engineers, New Orleans District issued a Mississippi and Louisiana Estaurine Areas Project Information Sheet, which summarized the current status of the project, as follows:

Work on the study was initiated on October 1, 1977. Fiscal year 1978 funds were used to conduct a field reconnaissance of the area by an interdisciplinary team on November 7 and 11, 1977. Initial public meetings were held in Gulfport and New Orleans on February 1 and 9, 1978, respectively. Coordination meetings were held with the U.S. Fish and Wildlife Service and Corps of Engineers, Mobile District. Fiscal year 1979 funds were used to initiate preliminary planning and preparation of a reconnaissance (Stage I) report. Currently underway are reconnaissance scope studies to determine the engineering feasibility, environmental acceptability, and economic justification of the freshwater diversion measures. The U.S. Fish and Wildlife Service is currently preparing a report on environmental base conditions and future conditions, optimum environmental requirements, the relationship between freshwater inputs and increased productivity of the fish and wildlife resources, and the fish and wildlife benefits that could be expected.

The project was funded for fiscal year 1980, and funding for fiscal year 1981 is expected to be approved, as requested. Efforts continue with the U.S. Army Corps of Engineers, members of Congress, and other interested parties. For example, concerted efforts were made to insure proper turnout for the 1978 public hearings in Gulfport and New Orleans. Not only was it considered important to the continuation of the project to have a strong supportive group in the audience, but it was also necessary to have a sufficient number of statements made (written and oral).

On February 22, 1980, a meeting was held in New Orleans with the U.S. Army Corps of Engineers Project Staff to insure continuation of interest, pledge of support, and review of the status and planned future efforts. On April 23, 1980 the Corps of Engineers New Orleans District, made a presentation in which it reviewed "our" project with two other freshwater studies. The thrust of this is to tie together several programs that have a common purpose, although the areas may differ somewhat. The Mississippi and Louisiana Estuarine Areas Study encompasses Hydrologic Unit I and the Mississippi Sound. The other studies are west of Hydrologic Unit I.

A planning aid report on the Mississippi and Louisiana Estuarine Area Study, (Fruge and Ruelle 1980), prepared by the Fish and Wildlife Service for the New Orleans District Corps states that the introduction of supplemental fresh water from the Mississippi River is expected to provide monetary benefits to fish and wildlife totaling between $4.4 million and $5.2 million annually. In addition, it was stated that the diversion is also expected to substantially reduce the serious loss of marsh presently being experienced in the Louisiana portion of the study area as a result of salt-water intrusion, subsidence, and erosion.

Seven years of effort have been expended on this project by many people. It is estimated that before fresh water can flow into the estuarine areas, another eight to ten years of effort and time will elapse. Fifteen years is a long time to keep an informal group together, with no monetary renumeration, motivated for a single purpose. It takes dedication, organization, planning, pursuasive leadership, and perseverence.

CONCLUSIONS

Although no conclusions can yet be drawn because the project has a long way to go before it is completed, some observations can be made. Success of the project can only be determined by the actual flow of fresh water into the estuaries, when and where needed, and with proper monitoring to assess the results of such actions.

Most of that which remains to be done is in the hands of the U.S. Army Corps of Engineers, the several local, state and Federal fish and wildlife agencies, and the U.S. Congress. Our task force will support and assist wherever possible. We will remain associated with the project until that "sweet water" flows.

Although everything we did was not the optimum approach, we were able to modify our plans where necessary and to keep the project organized on a going basis. We believe that the methodology described in this paper is worthy of consideration by others who plan to undertake the management, planning, and organization of a large scale project. The basic problem of the need for fresh water was alluded to back in 1904 and 1906 in the first (and second) annual report(s) of the Oyster Commission of Louisiana. Compared to the year 1904, the seven years on the project with eight to ten more to go does not appear quite so long in duration.

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AN OVERVIEW OF TEXAS LAW, POLICY, AND AGENCY ACTIONS CONCERNING ESTUARINE INFLOW

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ABSTRACT

With passage of Senate Bill 137 by the Texas Legislature in 1975, Texas water law finally recognized the need to preserve estuarine inflow and authorized studies to determine inflow needs. The Act's legislative history is presented along with a review of related water law. The availibility of applicable law and data has not resulted in development of an active policy or in strong agency action to preserve estuarine inflows, however. Examples are drawn from Texas Water Commission files with emphasis on Palmetto Bend Reservoir (Lake Texana), Choke Canyon Reservoir and Coleto Creek Cooling Pond permits. Also discussed are the shortlived attempt of the Texas Parks and Wildlife Department to participate in water rights permit hearings and adjudication, the Texas Water Development Board's draft "Texas Water Plan" (1977) as it relates to estuarine inflows, and the treatment of estuarine inflow preservation in Texas coastal management plan documents. Remedial actions are recommended.

INTRODUCTION

"Texas water policy has been influenced by the Civil Law of Spain, and Mexico, the Common Law of England through reception statutes, the enactments of the Republic of Texas, and later by those of the Texas Legislature" (Yarbrough 1968). The Texas Legislature borrowed statutory concepts and procedures from Nebraska, Colorado, Wyoming, and other arid western states. Riparian and appropriation doctrines were employed. With the creation of the Board of Water Engineers, in 1913, a permit system which continues until this day was established (Texas Society of Professional Engineers and Texas Section of the American Society of Civil Engineers 1974). Ground water and diffused surface water are the property of the landowner, however, Section 11,021 of the Texas Water Code provides:

"The water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the storm water, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression and watershed is the property of the state."

The original purpose of Texas water rights statutes was to provide for orderly and peaceful distribution of surface water among the State's citizens. Beneficial use requirements and ranking of priority among competing uses are recognized in Texas statutes. Water flowing unused to the Gulf of Mexico was (and still is in some circles considered to be wasted. However, in view of scientific discoveries to the contrary and the importance of sport and commercial fishing industries to the Texas economy over $563 million annually direct and indirect gross business (Texas Department of Water Resources 1979a), Texas water law has been expanded to include recognition of the importance of estuarine inflow.

Texas agencies responsible for water have undergone numerous changes in name, structure and duties. Functions of the State now include administration of water rights, protection of water quality, promotion of water development, preparation of a statewide water plan, and maintenance of the proper ecological environment of bays and estuaries. Senate Bill 1139 by the 65th session of the Texas Legislature reorganized the functions among the water agencies, abolished the Water Quality Board, transferred executive functions to the Department of Water Resources, replaced the Water Rights Commission with the Water Commission within the Department as the judicial arm of the agency and incorporated the Water Development Board in the Department as the agency's policy branch (Texas Natural Resources Council 1978). River authorities, water districts and cities also contribute significantly to water resources planning and development on the State level.

Average annual runoff in Texas is 49 million acre-feet (60.5 x 10^9 m^3). Current annual water use in Texas is approximately 17.3 million acre-feet (21.3 x 10^9 m^3) of which only 5 million acre-feet (6.2 x 10^9 m^3) are derived from surface water sources, however, the dependable yield from surface and groundwater sources without mining aquifiers is only 15.1 million acre-feet (18.6 x 10^9 m^3) per year. Projected water requirements for domestic, municipal, industrial, and irrigation uses are 27 million acre-feet (33.3 x 10^9 m^3) and 39.6 million acre-feet (48.9 x 10^9 m^3) in the years 2000 and 2030 respectively (Texas Department of Water Resources 1979b).

Historical 1941-1976) freshwater inflows (excluding direct precipitation) to the major Texas estuaries (excluding Laguna Madre) average about 29 million acre-feet (35.8 x 10^9 m^3) annually (Texas Department of Water Resources 1979a). Current permitted diversions for several major river systems nearly equal or exceed the mean annual discharge (Texas Natural Resources Council 1978; Texas Department of Water Resources 1980). Present rates of diversion are usually well below the permitted level, however, the bays would suffer severely during drought periods. As water requirements for inland needs reach the developable supply of contributing river basins, the potential exists for substantial alteration of the freshwater inflow regimes to estuaries (Texas Water Development Board 1977).

DISCUSSION

LEGISLATION

Following the drought of the 1950's, Governor Price Daniel asked a special legislative session to create a statewide water planning agency (General and Special Laws, Texas 1957a,b). The resultant Water Planning Act of 1957 established the Water Resources Planning Division within the Board of Water Engineers. This act was the first step toward development of a comprehensive statewide water plan, and though aimed primarily at development of storage, it did direct study of "other" beneficial uses of water. Planning duties were later placed within the Water Development Board.

After defeat by voters of a proposed constitutional amendment providing for financing of the Texas Water Plan and expansion of the powers of the Water Development Board, the 61st Legislature established a study committee to investigate water development planning including the ecological effects from implementation of the State water plant (Texas Water Resources Study Committee n.d.). The committee found the proposed plan not to be flexible as mandated by statute, no assurance by the Water Development Board for consideration of the environment, and substantial public concern for assuring adequate freshwater inflow to estuaries. Appendix A of the Committee report contained proposed legislation to authorize the Water Rights Commission, after proper hearing and study, to allocate quantities of water it considered necessary to maintain the proper balance of fresh and salt water in bays and estuaries, such allocation not to interfere or adversely affect prior appropriations.

The 61st Texas Legislature also passed Senate Concurrent Resolution 38 which declared the policy of the State of Texas to protect public interest in coastal resources including estuaries and directed the Interagency Natural Resources Council to coordinate studies of coastal resource problems (Texas Coastal and Marine Council 1979). Studies and reports resulting from this resolution have served as the basis for much legislation and policy modification in (Texas since 1969 Texas Coastal and Marine Council 1979).

Legislation concerning reservation of freshwater inflow drafted by the Texas Water Resources Study Committee was not adopted by the 62nd Texas Legislature in 1971. Johnson (1973) reports the Water Rights Commission at a later date expressed an opinion that such legislation was not necessary as the general grant of powers to it is sufficiently broad to accomplish this purpose. The 62nd Texas Legislature did, however, extensively revise the Texas Water Code and in so doing mandated that consideration be given in the water plan to the effect of upstream development on the bays and estuaries (Texas Water Code Sec. 16.061 [d]).

Senate Concurrent Resolution 101 of the 63rd Texas Legislature (1973), and Senate Resolution 267 and House Separate Resolution 83 of the 64th Texas Legislature (1974) (Texas Coastal and Marine Council 1979) contain virtually identical wording stating the need for freshwater inflow to maintain estuaries and the inherent right of Texans to use and enjoy such resources. As an outgrowth of these resolutions, the 64th Texas Legislature passed the most significant legislation to date for Texas concerning preservation of estuarine inflow-Senate Bill 137 by Schwartz et al. (General and Special Laws, Texas 1975). This act established maintenance of the proper ecological environment of the bays and estuaries as public policy (Texas Water Code Sec. 1.003), requires the Water Commission to assess freshwater inflow needs when considering applications for permits (Texas Water Code Sec. 11.147), and provided for studies of the effects of freshwater inflow to be completed by December 1979 by the Water Development Board (Texas Water Code Sec. 16.058).

In testimony before the Senate Committee on Natural Resources (March

12, 1975), Senator Schwartz stated that failure of the water plan to be accepted was due to failure to meet coastal needs and that the information to be developed on freshwater inflow needs was necessary for environmental impact statements and proper development of water resources. Mr. Lewis Seward, Water Development Board technical witness at the hearing, indicated that during preparation of the Texas Water Plan in 1965, the board found insufficient information on freshwater inflow needs and no coordinated study in progress to determine such needs. He further stated that the board and U.S. Geological Survey had started a cooperative date-gathering program on this matter in 1967.

Senate Bill 137 passed without dissent in the senate and cleared the house by a substantial majority (though it took two attempts to get out of the House Natural Resources Committee). The House added amendments insuring the Water Rights Commission could continue to exercise all jurisdiction on applications notwithstanding the status of the authorized studies (bill analysis for the Senate Committee on Natural Resources stated this intent) and excluding any additional authorization of funding for inflow studies (Texas House Journal 1975). The Senate refused the House amendments, and the Conference Committee report which adopted essentially the Senate version except for addition of a specific funding provision was enacted.

Senate Bill 137 removed any doubt concerning the authority of the Water Rights Commission (now Water Commission) to reserve unappropriated water for estuarine inflow and resolved at least in part many of the legal concerns expressed by Johnson (1973). No longer would preservation of estuarine inflow be dependent solely on interpretation of public trust doctrine, riparian rights, prior appropriation doctrine, or implied authority to preserve. Furthermore, attacks on preservation of inflow based on diversion requirements would no longer be viable if the Commission chose to reserve water.

Other portions of the Texas Water Code having significant bearing on preservation of freshwater inflow to estuaries are: section 11.021(b) declares imported water transported in navigable streams becomes property of the State; section 11.023 lists purposes for which water may be appropriated essentially any beneficial use and also allows for impoundment of arms, inlets and bays of the gulf; section 11.024 lists appropriation preferences as follows: (1) domestic and municipal; (2) industrial; (3) irrigation; (4) mining; (5) hydroelectric; (6) navigation; (7) recreation and pleasure; (8) other beneficial uses; section 11.030 provides forfeiture of water rights for willful nonuse; section 11.033 provides power of eminent domain to all political subdivisions of the State and constitutional agencies to recover from other uses water for domestic and municipal supply; sections 11.301 et. seq. provides for adjudication of existing water rights now in progress; section 12.112 exempts the Water Development Board and Texas Parks and Wildlife Department from any filing, recording or use fees for water appropriations; and section 16.052 forbids contemplation and formulation of a plan for interbasin transfer of water if water will be needed in the basin of origin within 50 years.

Texas water law pertaining to estuarine inflow is relatively untested, therefore, much is unsettled in this area of jurisprudence. Questions arise as to the priority of freshwater inflow, what constitutes consideration of inflow needs in assessing appropriation applications or upstream developments, and interbasin transfer if water is needed in the basin or origin for estuarine inflow. What is the standing of freshwater inflow needs in basins already fully appropriated, particularly after adjudication has been completed? Should interstate importation of water and construction of storage for meeting estuarine inflow needs be considered feasible if such water supplies can be easily condemned for municipal purposes? Is additional clarification by the Legislature needed? A review of agency actions and policy should shed some light on these matters.

AGENCY ACTION AND POLICY

Water Rights

The first significant consideration of estuarine inflow in a water rights application occurred prior to passage of Senate Bill 137 and primarily involved academic study rather than long-term preservation of freshwater inflows per se. The Texas Water Development Board (1972) requested permission to use water from Palmetto Bend Reservoir (a joint project with the Lavaca-Navidad River Authority now named Lake Texana) for inflow effect studies to develop a program as required for the Texas Water Plan. The selected release program was not to constitute a permanent right in reservoir yield. Protestants to the application attacked this request, primarily questioning the great cost for an irreversible environmental experiment (Shannon 1972).

The Water Rights Commission (McDaniels 1972) wrote the Board stating that using all of the testimony presented in public hearing indicated the requirements for maintenance of the estuary system downstream from Palmetto Bend are unknown and questioned the justification for issuance of a permit if the demands of the estuary would reduce the yield of the project. The Texas Water Development Board (1972) responded by reiterating that no permanent right on reservoir yield was to be perfected by the release program and that the project was not adverse to the bay based on previous studies and studies in progress. The Water Rights Commission issued the permit on October 3, 1972 and as revised on May 9, 1979 allows the Water Development Board to use its share of the annual firm yield (43,000 acre-feet or 5.3 x 10^7 m^3) for estuarine inflow studies until such water has been contracted for other uses.

The Water Rights Commission again dealt with estuarine inflows when considering the application by the City of Corpus Christi and the Nueces River Authority for water rights to Choke Canyon Reservoir. The Choke Canyon Reservoir site itself had been chosen over a downstream site partially to reduce adverse effects on the Corpus Christi estuary. Also, by letter of February 19, 1974 to the U.S. Bureau of Reclamation, the City of Corpus Christi suggested releases of 151,000 acre-feet (1.9 x $108/m^3$) per year from their water system for estuarine maintenance after completion of Choke Canyon Reservoir (Towsend 1974).

Testimony on the effects of estuarine inflow was given at the public hearing before the Water Rights Commission by Al Hill of the U.S. Bureau of Reclamation (now Water and Power Resources Service).

Mr. Hill testified that the effects of Choke Canyon Reservoir on the Corpus Christi Bay estuary were unknown (Texas Water Rights Commission 1976a). He further stated that the 151,000 acre-feet (1.9×10^8 m^3) per year figure for estuarine inflow was derived by calculating the expected effluent return flow from use of the entire 252,000 acre feet (3.1×10^8 m^3) firm yield of Lake Corpus Christi and Choke Canyon Reservoir (Texas Water Rights Commission, 1976b) was hardly a scientific method of determining inflow needs!

The Texas Parks and Wildlife Department was vitally interested in reservation of sufficient freshwater inflow to Corpus Christi Bay and therefore via letter of September 3, 1976 and meetings on September 1 and 7, the department sought results of Water Development Board studies on inflow needs (Garrison 1976). The exact informational needs of the department were not met. The Department (letter of September 13, 1976) requested that the Water Rights Commission include permit provisions to provide whatever water in addition to 151,000 acre-feet (1.9×10^8 m^3) per annum was needed, for estuarine inflow (Garrison 1976b). The Water Rights Commission (letter of September 20, 1976) notified the Department that its comments were received too late for consideration but that the Commission did hear extensive testimony on the effects of Choke Canyon Reservoir on Corpus Christi Bay (Schneider 1976).

Permit No. 3358 granted on October 12, 1976 requires that upon filling, Choke Canyon Reservoir - Lake Corpus Christi System shall return flows to Corpus Christi Bay and other estuaries. The permit further states that water for estuaries shall be released in such quantities and in accordance with such operational procedures as may be ordered by the Commission.

The Texas Department of Water Resources (1979a) recommended subsistence level annual inflow gauged and ungauged from the Nueces Basin for the Nueces-Corpus Christi Bay Estuary is 397,000 acre-feet (4.9×10^8 m^3). The projected average combined Nueces River inflows with full use of Lake Corpus Christi and Choke Canyon (under year 2010 conditions) (U.S. Bureau of Reclamation 1974) will fall short of this amount (the current median annual inflow is also below this amount and fluctuations may be beneficial to estuarine productivity). Permit No. 3358 therefore does not assure adequate estuarine inflow. Furthermore, a spokesman for the Department of Water Resources has indicated that in periods of severe drought, people and industries will probably receive the water reserved for estuarine inflow (Palmer 1980), and indeed the Water Commission has powers to allocate among uses during periods of shortage.

The Texas Parks and Wildlife Department took a more active role regarding the application(s) of the Guadalupe-Blanco River Authority and Central Power and Light Company for the Coleto Creek Cooling Pond, filing a protest seeking to preserve instream flow and estuarine inflow for fisheries. The Water Rights Commission on February 14, 1977 in considering a continuance requested by the Department indicated it had recently been encouraging participation by the Department and wished to give it every opportunity for an adequate hearing. Because this was the first time the Texas Parks and Wildlife Department had formally filed a protest on a major application, the Commission believed it might have far reaching effect on State water policy. The Department reached a settlement with the applicants in regard to base flow releases (and did not pursue estuarine inflow issues) before the commission reconsidered this matter in a public hearing on February 28, and March 1, 1977 therefore, little if any policy effects occurred.

While preparing for participation in the Coleto Creek hearing, the Texas Parks and Wildlife Department learned that Jack Nelson, Water Development Board Environmental Division Chief, was to testify for the applicants in regard to estuarine inflow effects. A request for materials on estuarine inflow upon which Mr. Nelson was to testify was at first refused and the data provided only after the Department filed a request for commission and subpoena with the Water Rights Commission on February 22, 1977.

On March 1, 1977, Mr. Nelson testified at great length before the Water Rights Commission in regard to the Water Development Board's inflow studies. He indicated that San Antonio Bay needs 1.2 million acre-feet (1.5 x 10^9 m^3) of fresh water per year and because the proposed permit would allow consumption of only a fraction of this amount, it was inconsequential. Mr. Mosley of Central Power and Light had earlier testified the project would have minimal effect since it would reduce inflow to San Antonio Bay by only 0.8 percent. This same type of analysis was often employed by the Water Rights Commission staff.

Mr. Nelson did make a somewhat startling disclosure in his testimony (Coleto Creek Cooling Project Hearing Record pp. 258-259): "I would like to say that we would have had that (sic. San Antonio Bay inflow study) completed Mr. Chairman, except we went into revision of the Texas Water Plan and that went on the back burner."

A Texas Water Rights Commission staff memorandum (November 12, 1976b) states the Technical Service Division using their "Water Availability Model" estimated an average of 855,089 acre-feet (10.6 x 10^8 m^3) per year, ranging from a minimum of 11,938 acre-feet (1.5 x 10^7 m^3) to a maximum of 2.2 million acre-feet (2.7 x 10^9 m^3) as available for appropriation from the Guadalupe River at the diversion point for the Coleto Creek Reservoir. This is the total flow of the river remaining after permitted diversions and reflects the view prevailing in the Water Rights Commission staff that reservation of flows for estuarine inflow is not mandatory.

In granting a permit(s) for Coleto Creek Cooling Pond, the Water Rights Commission (April 25, 1977) assessed effects on San Antonio Bay as minimal. The cumulative effect upon San Antonio Bay of water appropriations was given little if any real consideration.

The Texas Parks and Wildlife Department is dependent upon the Attorney General's Office for legal counsel and by letter of September 15, 1976 requested advice from the Attorney General on options to insure freshwater flows to maintain viable sport fisheries. The Texas Parks and Wildlife Commission was advised via memorandum of December 1, 1976 (Caroom and Newsom 1976) to participate in adjudication because once finalized by the courts, adjudication of water rights could be final and conclusive. The course of action recommended (to preserve instream flows) was to claim a reserved right of water (riparian right) held in trust for the benefit of all citizens.

This reserved right would date back to the State's creation when it assumed ownership of water. It was pointed out that any appropriation of water for recreation and fisheries would rank at the bottom of the statutory list of water use priorities. The Texas Parks and Wildlife Commission was further advised that: "Because the Water Rights Commission sits as an adjudicatory body on permits, it is difficult for them to advocate the needs of fish and wildlife on behalf of the State." (Caroom and Newsom 1976).

By letter of January 28, 1977, the Texas Parks and Wildlife Department directed the Attorney General's Office to pursue reservation of water rights for fish and wildlife in the Medina River adjudication.

A claim and a contest were filed on January 28 and 31, 1977, respectively, by the Texas Parks and Wildlife Department claiming 2.07 million acre-feet (2.6×10^9 m^3) per annum freshwater inflow (the average historical inflow) to San Antonio Bay. This amount was within the range found by Childress et al. (1975) to be needed for preservation of the San Antonio Bay fishery.

Newsom (1977) in a brief to the Texas Parks and Wildlife Commission presented various options for securing estuarine inflow. The appropriations route was thought unworkable because, (1) diversion requirements under common law and virtually every jurisdiction in the country would be an unbearable burden, (2) the Commission could not afford storage facilities, (3) the low priority of use, and (4) the needed quantity of water was not available for appropriation in some river basins.

Protesting individual applications was also thought to be impractical. Of special interest are Newsom's statements on page 3:

> "Indeed, the truth of the matter is that the bays and estuaries are being nickeled and dimed to death with even minor appropriations. A percentage reduction here and a percentage reduction there may seem insubstantial to water development engineers; yet the actual impact upon both short and long term fisheries' productivity may be great."

and on page 5:

> That the fish and wildlife resources of the state are significant and important natural resources and accordingly within the public trust of the state to preserve and protect is a proposition palatable to both existing statutory authority and judicially created case law. The principal case in water law and water rights in this state, Motl v. Boyd, 116 Tex. 82, 286 S.W. 458 (1926), rests upon the holding that the distribution and recognition of water rights must be consistent with the public trust shared by officials of the state.

Opposition to the Texas Parks and Wildlife Department's participation in adjudication arose among water rights permit holders, particularly those fearful of forfeiture due to nonuse. The Bexar-Medina-Atascosa Water Improvement District Number One (1977) circulated a resolution decrying such participation, and water development and supply agency representatives were openly hostile to Texas Parks and Wildlife Department representatives at a March 15, 1977 meeting held at the San Antonio River Authority's headquarters to discuss the status of the claim and contest. In view of such turmoil, the Texas Parks and Wildlife Commission reconsidered involvement in adjudication during a special public hearing on March 18, 1977. Commissioner Bob Burleson (Texas Parks and Wildlife Department 1977:90-91) expressed concern that pursuing water rights through adjudication would risk department budget appropriations by the legislature for other programs. Indeed, such threats were made (Burleson, Pers. Comm. July 7, 1980).

The Texas Parks and Wildlife Commission opted to withdraw from adjudication but asked the Attorney General's Office to draft suggested language reserving public interest in water for inclusion by the Water Rights Commission in permits. Newsom (1977) offered the following:

> "This determination, and each and all claims of water rights recognized herein are subject to the continuing right of the sovereign, State of Texas, to provide an adequate supply of fresh water for the preservation and conservation of the public's fish and wildlife resources."

Though the Texas Parks and Wildlife Commission did not pursue this matter (and the Department discontinued nearly all activities to preserve estuarine inflows), language to accomplish the same purpose surfaced in the Department of Water Resources. A memorandum by Chief Counsel Bigelow (Texas Department of Water Resources 1978) concerning a Gulf Oil Company application for a substantial diversion from the lower Guadalupe River states that Water Commission examiners have been recommending the following clause to comply with the statutory mandate to assess the effect of applications on bays and estuaries:

> "This permit is issued subject to the Commission's continuing authority to require permittee to cease direct diversions to accommodate the needs of the needs of the ___________Bay System as determined by the Department of Water Resources."

Mr. Bigelow found that the department's planning division intended to "do nothing" regarding the significant bay and estuary question involved by the Gulf Oil Company application and recommended that the department take a position urging the Water Commission to include the above language in a permit if granted. Permit 3606 issued to Gulf Oil Company on October 16, 1978 merely stated the commission has assessed the effects of issuance on the bays and estuaries.

The Water Commission has no real policy on preservation of freshwater inflow to estuaries. In fact they have failed to develop such policy as requested by petitions dated January 6, 1978 and March 15, 1978 by the Wildlife Management Institute. The latter request merely asked for procedural rules to enter Department of Water Resource estimates of inflow needs and water availability data into the record of all permit hearings.

The Department of Water Resources has produced the estuarine inflow studies required by Senate Bill 137 and briefed the Water Code Subcommittee of the House Natural Resources Committee on March 14, 1980. These studies have resulted in excellent data on which to base reservation of freshwater inflows. Alternatives suggested for meeting inflow needs were (1) granting of water rights for surface water diversion and/or storage consistant with estuarine needs and (2)water resource development in those basins estimated to have surplus water to meet multiple purposes including those of water deficient basins (Texas Department of Water Resources 1980). Upon questioning by the Committee, Mr. Bigelow (Water Code Subcommittee 1980) allowed that legislative guidance was needed by the Water Commisssion and the Department of Water Resources as to how they should take into account estuarine inflow needs, i.e. deny permits, condition permits, etc.

TEXAS WATER PLAN

Development of the Texas Water Plan also has ramifications for preservation of estuarine inflow. Chapman (1971) provides a review of a 1968 version of the plan which would supplement inflow to various bays with water from out of state, substantial curtailment of estuarine inflow would occur due to local development. As indicated earlier, failure to adequately address estuarine needs has hampered development of an acceptable plan.

In 1977, the Texas Water Development Board circulated a draft plan entitled Continuing Water Resources Planning and Development for Texas (Vol. I and II). Although the 1977 draft is bolstered by preliminary information from the estuarine inflow studies mandated by Senate Bill 137, it fails to provide any meaningful plan to assure estuarine inflow but does propose to meet "needs" for municipal expansion. The Water Development Board once again appears preoccupied with facility development and loan fund activity as found earlier by the Texas Water Resources Study Committee (n.d.). Due to Mr. Nelson's revelations before the Water Rights Commission regarding estuarine inflow studies being placed on the back burner to get out the water plan, little credibility can be afforded the board's consideration of the needs of estuaries.

One can only guess at how the Water Development Board expects to fund any storage or import of water to meet estuarine needs. If the board's position that mitigation of fish and wildlife losses from water resource developments be paid by Federal and State fish and wildlife agencies (Texas Department of Water Resources 1979a) is any indication, perhaps the board would expect fishermen to pay for replacing historic flows to the bays.

In what may not have been in too facetious a vein,(Department of Water Resources 1979c) listed "get the environmentalists off our backs" among four points to assure adequate water supplies. If this view prevails in the Department, then little more than a straight economic balancing act can be expected in consideration of water for estuaries. Such an approach is in keeping with the Governor's Water Resource and Conservation Task Force (n.d.) recommendation that study of freshwater requirements of estuaries was necessary for economic analysis purposes in resolving tradeoffs with competion uses.

TEXAS COASTAL MANAGEMENT PLAN

The other major state planning effort having concern for estuarine inflows has been coastal zone management. Several important pieces of State legislation were passed in the early 1970's to prepare Texas for development of a meaningful coastal management plan. The plan as submitted by the Texas General Land Office (1978) failed to provide any substantial improvement in protection of public coastal resources, and in regard to preservation of estuarine inflows, it painted an erroneous picture of the state of affairs. Among the mistakes was an assertion that Texas Parks and Wildlife Department actively participates before the Water Rights Commission and that great weight is afforded its testimony. This information appears to have been lifted almost verbatum from Texas Coastal Issues, A Preliminary Report (Texas Natural Resources Council 1978). A revised coastal program (Clements, 1979) states the Water Commission may deny a permit if detrimental to estuaries and that in addition to Texas Parks and Wildlife Department review, the Department of Water Resources makes a detailed assessment of each application's effect on estuaries. Neither plan contains concrete provisions for estuarine inflow preservation. Another draft plan is to be issued in 1980.

CONCLUSIONS

While Texas possesses an excellent data base on estuarine inflow needs and powers granted the Water Commission appear sufficiently broad to allow reservation from appropriation those quantities of water required and still available, agency actions and policy do not reflect a comprehensive program to provide freshwater inflow to estuaries. In particular, no consideration is given to the cumulative effect of water appropriation. Also, no program to provide inflow in overappropriated basins has been enacted. Though additional direction from the legislature as suggested by Bigelow (Water Code Subcommittee 1980) may be helpful (and in the end necessary), other remedies are available.

To date no strong advocacy position and testimony has been presented before the Water Commission in support of reserving water for estuarine inflow. A protest to a major permit, including assessment of effects on bays and estuaries as a major issue, could result in significant policy changes.

Rule making is another avenue for reform which can be instigated by agencies, conservation and fishing groups, and individuals. Rules on presentation of existing inflow needs data and reservation of freshwater inflow should be developed for assessing new applications and for remaining adjudications. Rules on term and conditional permits may be in order for basins now having annual or seasonal surpluses of water.

In basins already over allocated (including those already adjudicated), diligence should be exercised by the Water Commission in revoking permits for nonuse. Substantial quantities of water may be freed for estuarine inflow reservation by this method. Cancellation upon expiration of term permits may also free a limited amount of water. It is doubtful that taking of perfected private water rights (particularly adjudicated rights) for estuarine inflow could be accomplished or is even desirable.

The Texas Parks and Wildlife Department is responsible for protection and enhancement of fish and wildlife resources and is therefore the proper agency of the State to take an advocacy role in estuarine inflow preservation. It should become active in pursuing reservation of freshwater inflow to estuaries and in development of the Texas Water Plan.

Application for water rights, development of storage facilities, and interbasin transfer of water for fisheries preservation appear impractical due to cost, threat of loss through condemnation, and low priority in time and use. Also, participation by fisheries interests in all permit hearings would constitute an unreasonable burden.

A State policy of continued industrial and municipal growth can be expected to further reduce the availability of freshwater for estuaries.

DISCUSSION

Comment: Bill Farguhar, Chairman of the River Authorities Group organization in Texas: I have no authority whatsoever to speak for any other river authority here this afternoon. The point I would like to make to all of you, is that I have worked with these other river authority general managers for 10 to 12 years. I've been their chairman for a couple of years. I know them pretty well. A great majority of them are reasonable men. And you can talk to them. I have come away from this with a definite impression that most of you who are interested in gaining inflows for the estuaries prefer to attack rather than to talk. Let me recommend to you that you drop your confrontation and attack tactics and come and sit down with us--those of you who have official responsibilities in connection with freshwater inflows. I think the majority of us are reasonable men. We would like to talk to you about it. We are just as interested in our estuaries as you are. Once these studies are in, we'll be happy to sit down with anyone who is interested in the agency or the water board and work out an accurate solution and actually support it before the Water Commission. Again, let me advise you to come and talk to us instead of attacking us. Thank you.

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FRESHWATER INFLOW TO THE COLUMBIA RIVER ESTUARY:

A NORTHWEST REGIONAL MANAGEMENT ISSUE

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ABSTRACT

The Columbia River is the largest freshwater drainage system on the Pacific coast of North America, yet less is known about its estuary than about any other of comparable size in the United States. With many conflicting uses for its water, the Columbia River system is unable to meet all the demands for water during periods of reduced discharge. The Pacific Northwest River Basins Commission, as the interagency regional planning organization dealing with water resource planning in the Columbia River system, has undertaken two programs designed to deal directly with this issue of instream flows. The Regional Tradeoffs Analysis Program will be evaluating and documenting competition among various water uses and the economic, environmental, and social benefits and costs (tradeoffs) which would result from alternative levels of use for competing purposes. The Columbia River Estuary Data Development Program is a $6.2 million special program with a dual purpose: to increase the understanding of the Columbia River estuary as a system, and to acquire information needed for making specific land/water management decisions. It is anticipated that the inclusion of information provided by this interdisciplinary research effort in the Regional Tradeoffs Analysis Program will provide a solid basis for prodicting impacts of varying instream flows on the Columbia River estuary.

INTRODUCTION

THE REGION

The physical geography of the Pacific Northwest is dominated by three mountain ranges which generally have a north to south orientation. The westernmost mountains are the Coast Range. Although most of these peaks are below 3,000 feet in elevation, a few exceed 7,000 feet on the Olympic Peninsula. The next range of mountains to the east are the Cascades, the most visually prominent mountains in most of Oregon and Washington as well as the dominant climatic control over most of this region. The Cascade crest varies between 4,000 and 6,000 feet in elevation. This mountain range also includes the only volcanically active region in the conterminous United States. Several of the volcanic peaks exceed 10,000 feet with Mount Rainer dominating the chain to the north, while Mount St. Helens dominates the news. Still further to the east, in Idaho, Montana, and Wyoming are the Northern Rocky Mountains with a few peaks exceeding 12,000 feet in elevation.

The climate of the region is best described as both seasonally and geographically variable. Precipitation is concentrated in the period of December to April, with little or none being measured from July through September. A "normal" summer west of the Cascades may have 70 to 80 continuous days of no precipitation, resulting in a summer drought despite annual averages of 24 to over 200 inches of precipitation.

Geographically the climate is much influenced by the mountain ranges. The prevailing winds bring considerable moisture into the region from the Pacific Ocean. Much of this moisture is then dropped on the western slopes of the mountains as the air masses are adiabatically cooled, leaving the eastern slopes much dryer. Despite the reputation the Northwest has for receiving large amounts of precipitation, more than half of the Columbia River drainage basin receives less than 24 inches of precipitation annually (Pacific Northwest River Basins Commission 1979).

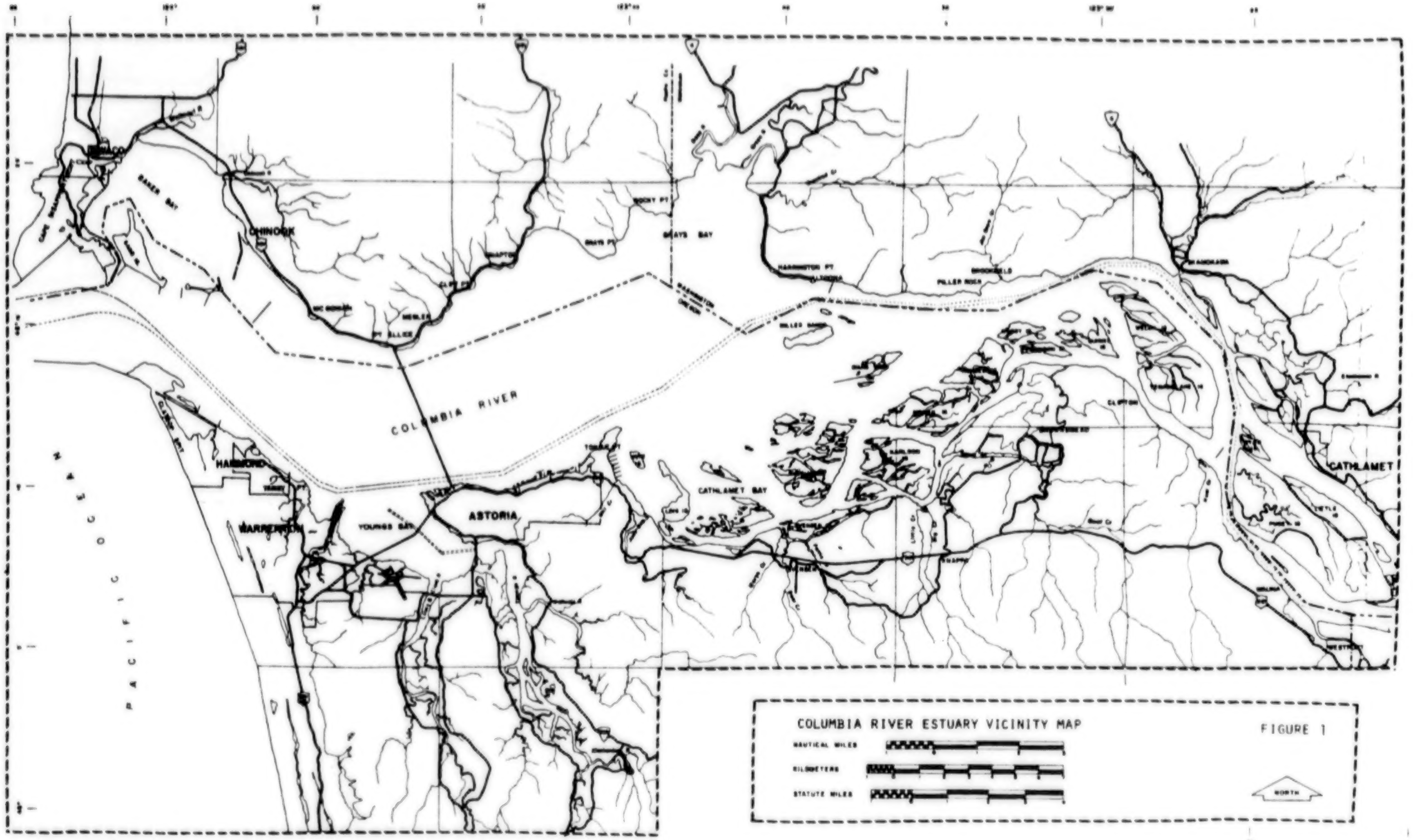
THE RIVER

The Columbia River system consists of the Columbia River, one major tributary (the Snake River), and many lesser tributaries. The Columbia River has its origin in Columbia Lake in the Canadian Rockies. From there the river follows a circuitous route for over 1,200 miles, including 480 miles in Canada, to the Pacific Ocean. The river drains a total of about 260,000 square miles, of which about 85 percent, or 219,000 square miles, is in the United States. The Snake River drains about 49 percent of the portion located in the United States or about 108,000 square miles. Despite the fact that more than half of its drainage basin would be classified as semi-arid to arid, the Columbia River has an average annual total discharge 10 times that of the Colorado River and 2.5 times that of the Nile River (Pacific Northwest River Basins Commission 1979).

With 13 mainstream dams and over 100 dams on its tributaries, much of the variability in discharge rates has been eliminated. During the annual spring freshet, which typically peaks in June, the streamflow now rarely exceeds 600,000 cfs. Minimum flows usually occur in the fall with discharge rates rarely dropping below 150,000 cfs. The annual average streamflows are typically around 200,000 cfs. Historically the extremes have ranged from a high of 1,240,000 cfs in 1894 to a low of only 65,000 cfs during an extended drought in 1931 (U.S. Army Corps of Engineers 1963).

The extent of the Columbia River estuary is highly dependent on how it is defined. If one bases this definition on the extent of tidal influence, the estuary could be said to e xtend over 100 miles inland. If, on the other hand, one utilizes the encroachment of salt water to delineate the estuary, it would virtually disappear during the spring freshet. For management purposes the Columbia River estuary has been defined as the first 46 miles of the river, which corresponds rather closely to the uppermost point of current reversal from tidal influence during periods of "normal" flow and is administratively easy to locate as it corresponds to the eastern most end of Puget Island (Figure 1).

Using this definition, the Columbia River estuary has a surface area of approximately 150 square miles, making it the ninth largest



map furnished courtesy of the Columbia River Estuary Study Task Force

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Figure 1. Columbia River Estuary vicinity map.

estuary in the United States. Roughly 75 percent of the estuary lies in Oregon, the remainder in the State of Washington. Depths seldom exceed 60 feet, and in the middle and upper portions of the estuary are usually less than 30 feet outside the main channel (Columbia River Estuary Study Taskforce 1979).

Three zones have been identified in this estuary by Sims (1970). The upper estuary, above Harrington Point, is predominantly fresh water but with daily tidal current reversals during most of the year. This zone also contains most of the islands which are found in the estuary. The middle estuary, located between Youngs Bay and Harrington Point, is typically a zone of fresh and salt water mixing. The lower estuary, below Youngs Bay, is predominantly marine in character. These zones may have quite different salinity regimes than what was described according to the freshwater inflows to the estuary. During periods of very high discharge there may be no detectable salinity inside the mouth of the river, while during periods of very low discharge fairly high salinities may be found in the upper estuary. During the drought of 1976-1977, the Coast Guard aids to navigation maintenance team found acorn barnacles (Balanus sp.) attached to pilings as far upstream as Pillar Rock.

THE CONFLICTS

Although the Columbia River has a substantial total annual discharge, the discharge rate is characterized by large seasonal and annual variations. During the summer months, when instream flows are dwindling, the greatest demands are placed on the system by its users. It is the combination of lowered flows and peak demands that creates conflict.

AGRICULTURE

Agriculture in the Pacific Northwest ranks second only to forest products in regional economic importance. Irrigation demands account for more than 90 percent of the region's total water diversion and consumptive use (Pacific Northwest River Basins Commission 1979). Most of the presently, and potentially, irrigable land lies in the low rainfall areas east of the Cascades. With the high evaporation rates in this area, the estimated total annual water demand for irrigagation use is in excess of 35 million acre-feet. Over 90 percent of the demand is met with surface supplies during the summer months.

POWER GENERATION

Hydroelectric power generation provides about 80 percent of the region's electricity, with most of the remainder coming from thermal-electric plants. About 60 percent of the generating capacity planned or under construction is also hydroelectric. Except for reservoir evaporation losses (which can exceed 36 inches annually east of the Cascades) hydropower is generally considered a nonconsumptive instream water use (Pacific Northwest River Basins Commission 1979). The major impacts of hydropower operations on instream flows are (1) the smoothing, or reduction in variability, of discharge rates, and (2) the shifting of periods of high or low discharge to meet actual or anticipated power demands.

Thermal-electric power generation requires water principally for cooling. Water quality standards for discharge temperatures effectively preclude once-through cooling. As a result evaporative cooling is generally used and water use is almost totally consumptive. A typical

1,000 megawatt nuclear generating plant using existing technology will consume 15,000 to 20,000 acre-feet of water annually.

NAVIGATION

While only about three percent of the Nation's population lives in the Pacific Northwest, about six percent of the Nation's oceanborne commerce moves through Northwest ports. The ports on the Columbia River system handled 43,776,000 tons of commerce, or about 35 percent of the 126 million tons of waterborne commerce moved in the region in 1975 (U.S. Dept. of Commerce 1975).

The largest port on the Columbia River system, indeed the largest port in the Pacific Northwest in terms of total tonnage trans-shipped, is Portland, Oregon. To provide access to this port for deep draft vessels, the U.S. Army Corps of Engineers maintains a navigation channel in the Columbia River to a minimum depth of 40 feet for a total of 118 miles. The Corps of Engineers also maintains a shallower navigation channel from the Portland area to Pasco on the Columbia River, and to Lewiston, Idaho, on the Snake River; a total of 465 miles from the mouth of the Columbia and with a total rise of about 740 feet. The need to maintain minimum depths for navigation places additional demands for instream flows on the system, particularly during low flow periods.

FISHERIES

Regional water management agencies have typically devoted more attention to the anadromous fisheries than to those for non-migratory species. This is due to the economic and recreational importance of these fisheries, particularly the salmon and steelhead fisheries. Although the great Columbia River salmon runs (when millions of fish were harvested each year) are a thing of the past, there is still a substantial and very valuable fishery devoted to these fishes. Over eight million pounds of salmon and steelhead were landed from the Columbia River system in 1975 by the commercial fishery alone (Oregon Dept. of Fish and Wildlife/Washington Dept. of Fisheries 1976).

The peak migration periods for the returning adult salmonids and the seaward-bound young, or smolt, in the Columbia River are spring, summer, and early fall. During the latter parts of this period the migrants must compete for reduced instream flows with the other water uses already mentioned. Reduced instream flows result in a longer residence time for young fish with potentially greater exposure to predators and other hazards. For the returning adults the reduced flows may fail to trigger the upstream migration urge.

COLUMBIA RIVER ESTUARY

Considering the size of the estuary and its importance both environmentally and economically to the Columbia River system, surprisingly little is known about its components and processes. In particular the relationship of freshwater inflows to the functioning of the estuary is poorly understood. Some of the questions about these relationships which remain to be answered concern the effects of variations of instream flows on anadromous fishes; the effects of reduced peak flows on the mechanisms where detrital material is flushed into the system; and the effects of instream flows on sedimentation rates in the estuary.

MANAGEMENT APPROACHES

The Pacific Northwest River Basins Commission (PNRBC) is an interagency regional water resources planning organization formed in 1967 by Presidential Executive Order at the request of the governors of Wyoming, Idaho, Montana, Washington, and Oregon, and in accordance with the provisions of the Water Resources Planning Act of 1965. A principal goal of the PNRBC is to prepare and keep up to date, to the extent practicable, a comprehensive, coordinated joint plan (CCJP). The CCJP for the PNRBC was published as four volumes in 1979 (Pacific Northwest River Basins Commission 1979).

As part of this process of developing and maintaining a CCJP, the commission is authorized to conduct a Regional Tradeoffs Analysis Program designed to evaluate and document competition among various water uses and the economic, environmental, and social benefits and costs (tradeoffs) which would result from alternative levels of use for competing purposes. In June 1979, a work plan for conducting this Tradeoffs Analysis Program was approved by the commission and preliminary investigations were commenced. To date the emphasis of the program has been to document and begin the analysis of three major competing uses--hydroelectric power production, streamflow for anadromous salmonid fish migrations, and diversions for irrigation. Those analyses are not yet sufficiently detailed to provide a suitable basis for water management decisions.

Closely linked with the information needs for the Regional Tradeoffs Analysis Program will be the products from another commission program, the Columbia River Estuary Data Development Program (CREDDP). CREDDP is a 100 percent federally funded special study with a total budget of about \$6.25 million. Although a small appropriation (\$50,000) was made in the commission's FY78 budget for the purpose of developing a plan of study, the first major program activities began in FY79. The field research portion of the program began in October 1979, and the final products will be available by the end of FY 1984. Program participants include state and Federal agencies, universities, and private organizations having demonstrated particular expertise in certain technical subjects.

The purpose of this research program is twofold: to increase our understanding of the Columbia River estuary as a system, and to acquire information needed for land and water resource management decisions. In order to meet the information needs of a broad spectrum of interested groups as possible, CREDDP will provide three types of products: (1) a descriptive and quantitative understanding of the important estuarine physical and biological processes and properties, (2) a capacity to identify and predict the physical and biological results of alterations in stream flows and other estuarine modifications, and (3) certain specific management-oriented products beyond those required by (1) or (2) which were identified early in the program planning process. The program's elements were divided into 26 work units and a total of 28 separate contracts have been let for their accomplishment.

It can be anticipated that the inclusion of information developed in this interdisciplinary research program in the Regional Tradeoffs Analysis Program will provide a solid basis for predicting the impacts of instream flows in the Columbia River estuary system.

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SCIENTIFIC PROGRESS AND DETERIORATING ECOSYSTEMS

SAN FRANCISCO BAY AND THE 1970's

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ABSTRACT

This paper begins by recognizing some of the considerable progress made by planners, scientists, and environmental managers of the 1970's in identifying the uncertain and to a considerable degree unquantifiable, nature of bay/estuary ecosystems, and in offering improved prescriptions for their protection. At the same time, it observes--using San Francisco Bay by way of example--that this progress in understanding theory and making prescriptions has been accompanied by continued stressing of the bay systems and in some instances by their further deterioration. Finally, the paper merges scientific prescription with new institutionally bounded insights to suggest some initiatives to translate improvements in science and management theory into improvements in managing the San Francisco Bay/Delta ecosystem.

INTRODUCTION

An early signal for increased ecological emphasis in bays and foreshores came from California, first through the activities of the Save San Francisco Bay Association, 1965 to 1969, and later, in 1972, through the passage of Proposition 20--the Coastal Zone Initiative. At a national level, the National Environmental Policy Act (1970) followed the Clean Water Restoration Act of 1966 and the Estuary Protection Act of 1968, and was itself followed by the National Coastal Zone Management Act of 1972.

In Canada, the signals came later--perhaps culminating in Bill C-38, the act which amended the Canada Fisheries Act in 1977. As with most signals, a considerable amount of effort took place prior to that time but, in essence, it was those signals, and others like them, that released a tidal wave of dollars and scientists upon bays, estuaries and other coastal features.

In California, passage of the Coastal Zone Initiative, and of similar protective legislation, represented not as much a triumph of theoretical construct, or of analytical procedure, as a reorienting of metaphysical (value) base. Neither science nor scientists were the moving force (Healy 1978). People supported the Initiative (Proposition 20), and other environmentally oriented legislation of the 1970's, primarily because "things had gone too far"--because they knew a river, bay or ocean was there, and couldn't see it, becuase they could see it, and couldn't get to it, because they could smell it, and it smelled bad, because they swam in it, and got rashes, because they ate fish from it, and got sick. Similarly in the Thames River in England, the Willamette in Oregon, the Great Lakes, the Mediterranean Sea (more recently), and so on.

What this says--simply put--is that science is both directed and constrained to a considerable degree by the values and perceptions of the society in which it lives. Such a pronouncement is not surprising for scientists are products of their society, and it has long been recognized that scientific endeavor has three basic components: (A) a philosophical basis of value (termed metaphysics); (B) a formal system of logic (termed theory); and (C) practical methods of observation, testing, verification and analysis (termed procedure). It is treatment of value (A), or more correctly non-treatment of it, by contemporary science in bays and estuaries that is at the heart of many bay-impact problems today. This paper attempts to address that problem with specific application to San Francisco Bay (Meyer 1980b).

THE RUSH THAT FOLLOWED

Predictably, passage of enabling legislation, and the provision of significant amounts of monies, was accompanied by an expanded interest in the ecology of bays, estuaries and foreshores by both the bureaucrat and the scientist. Typical of early work is "The Water's Edge" by Ketchum et al. (1972) in the United States, and in Canada "Management of Coastal Resources in British Columbia" (BCLRSC 1977). The four volume compendium of proceedings from the Coastal Zone '78 Conference held in San Francisco provides testimony to both the breadth and diversity of interest/effort in coastal areas toward the end of the 1970's. Three general trends, at least, seem apparent during the 1970s.

First, at an institutional level, efforts were made to enhance cooperation and coordination between the many agencies and entities with jurisdiction and/or interest in bays and, more generally, along foreshores and coastlines. Commissions, councils, study teams, etc., were formed and have now been active in this regard for some years. Second, fueled by scientists in agencies, universities, etc., there was a strong move to understand bay systems. While this effort involved some theoretical development (B), it seems primarily to have been procedural (C) in nature. Science seemed primarily involved in observing, inventorying, and describing the constituents of bay systems, or systems' reactions to exogenously generated impact. Where theory was applied, it was most often theory developed es post facto for the study of earlier terrestrial or aquatic events. This is not surprising either, for science and bureaucracy traditionally both advance from what-we-know toward what-we-don't-know, sometimes in lockstep. Third, a consistent cry from bureaucrat and scientist alike during the 1970's was "we need to educate the public"--notwithstanding the public origins of the enabling legislation. This opinion seemed founded on the assumption that public understanding of the importance of bays and estuaries was a key to obtaining ecologically sensitive management and protection measures.

In sum, considerable cooperation, understanding, and education has taken place during the past decade. Sparked by an aware public, dedicated individuals, imaginative programming, and better budgets, capability in all three targeted areas (e.g., A, metaphysics; B, theory; and C, procedure) has advanced impressively. Yet the question must be asked: why is bay ecological deterioration continuing? Or, if we are doing so much better why are we doing so much worse? (Meyer 1980b)

San Francisco Bay provides an example worth analysis, because many historians hail the Save the Bay movement of the 1960's for bringing on the coastal zone management of the 1970's in California at least.

SAN FRANCISCO BAY AND THE ENVIRONMENTAL 1970's

As far as long term protection is concerned, the 1970's came and went without any improvement in San Francisco Bay's situation. If anything, it worsened. Definitely it worsened as far as freshwater inflow is concerned.

The 1970's started promisingly enough with the Porter-Cologne Act for water quality, the California Environmental Quality Act (CEQA), the National Environmental Policy Act (NEPA), and the Federal and state coastal management and clean water programs mentioned earlier. But they ended with the recommendations of the Governor's Commission to Review Water Rights being ignored; with an historic water right determination giving the bay no interim flows; with a 10-year Delta and Suisun Marsh water quality control "plan" that contains only token studies of the bay's needs, funded by upstream users; with researchers finding that 50 percent of the bay's adult striped bass population suffer from parasitism, lesions or other physiological problems; with the once famous Bay-Farallons Dungeness crab fishery in its 19th straight year of decline; and with the Peripheral Canal and the San Joaquin Valley drain each one decade closer to being operating realities for the already intensively developed Sacramento-San Joaquin River system (Davoren 1980). Then the 1980's started ambitiously, with Governor Jerry Brown signing SB 200 authorizing the Peripheral Canal and other projects on July 18 costing between $5 and $10 billion.

Farther upstream, not to be outdone, the renamed Federal Water and Power Resources Service (WPRS) closed out the 1970's promoting a post-year 2000 program to enlarge Lake Shasta by 350 percent. The water yield would come from capturing the unregulated flood flows that now flush the bay-delta--rarely, as in the winter of 1979-80--and carry nutrients and sediments to the ocean. The additional water would be used primarily for irrigation, which meets the historical interpretation of the state's beneficial use laws more appropriately than simply leaving it in the river for fish and other instream and estuarine purposes. Also in 1980, WPRS entered its 13th year of negotiations with the operators of one of the Nation's youngest, but largest, reclamation projects--the Westlands Water District. The task here is to convert annual contracts into long term contracts to: (1) establish the district's basic San Luis project entitlements, plus additional water the district believes it needs or is entitled to, and (2) to start construction planning for the San Luis (project) drain.

These two Federal projects, and many others existing and proposed, are affected by the Carter Administration's 1978 proposal to reauthorize the Central Valley Project (CVP) A major purpose of the reauthorization is to make it possible--fiscally, legally and operationally, as well as politically--for the Secretary of Interior and WPRS to meet the delta water quality standards set by the State Water Resources Control Board (CWRCB 1978b,c). The reauthorization should also settle some longstanding arguments about the Federal Government's responsibility for repelling saltwater intrusion in the delta (MacDiarmid 1976), which has been going on since 1957, and should expand the CVP's basic project purposes to include meeting fish and wildlife needs of the Central Valley (somehow overlooked since 1937).

All the studies, projects and decisions mentioned in the previous section somehow impinge upon the water flowing from the embattled Delta to San Francisco Bay, either its quantity or its quality or both. In contrast to the delta, and Suisun Marsh since 1978, there are simply no flow or salinity standards to assure the bay's inflows from the delta. The delta's flows to the bay have been reduced 60 to 70 percent by upstream water use, by inbasin bypasses, and by exports from the Sacramento-San Joaquin system to the Southern San Joaquin Valley, Kern County and Southern California (Davoren 1980).

There is no physical or legal limit to further reductions of delta outflow. There is continuous political and economic pressure for more upstream development and more exports There is no interim or minimum freshwater inflow protection for the bay now, despite the fact that the San Francisco Bay-Delta estuary is the largest and most valuable estuary on the West Coast of the contiguous 48 states (Conomos 1979; Seckler 1971; Hedgpeth 1979). Freshwater inflow is vital to the bay's biological, physical, chemical and hydraulic processes (Conomos 1979; Goldman 1979; Fischer et al. 1977; McCulloch et al. 1970).

THE METERED BAY TODAY

San Francisco Bay must depend upon the delta for 90 percent of its natural freshwater inflows from all sources. A useful question then, after 130 years of upstream water development and diversions and 29 years of pumped exports (Storm 1970), is "How much is left for the bay today?" Before any significant development upstream, say in 1850, rain and snowfall in a normal weather year provided flows of 30 to 31 million acre-feet (MAF) to the delta from the 59,000 square miles of the Central Valley basin. What got to the delta also got to the bay, minus evaporation and evapotranspiration, but in a far different manner than it gets to the bay today. Then the delta was a vast tangled marshland. Today it is 60 major leveed islands, hundreds of smaller islands, a small inland sea due to a drowned island, and 700 miles of navigation channels, sloughs and waterways.

Today the mythical normal weather year cited earlier brings to the bay only 9-12 MAF, possibly less (estimates vary). In the record drought year of 1977, only 3.5 million acre-feet reached the bay. But even this important benchmark number is estimated, not measured, by the Delta Outflow Index (DOI). The DOI was developed by the Water and Power Resources Service, formerly the Bureau of Reclamation, and the Department of Water Resources. It has been used by these two agencies since 1969 in joint operations studies, and has become the empiric number on delta outflow. Today it is used in delta standards setting and for other regulatory and technical purposes--although it is known to be weakest statistically in the wet and dry years when river regulation for ecological purposes is most critical (Davoren 1980).

The water development projects being planned today, primarily sponsored by the Federal and state water development and operation agencies (WPRS and DWR), will extract another 3 to 5 MAF per year, maybe more, from the flows reaching the bay year 2000. This brings the planned normal year range of delta outflow to the finger-counting stage of 4 to 10 MAF per year.

What happens to the bay in such a scenario is not known. Studies of this began in January 1980. Even the projections of the Department of Water Resources (presumably on the conservative side favoring more development, since the SWP is still short of delivering 2 MAF of the contract obligations DWR assumed originally to finance SWP constrution) place the outflow at Year 2000 level of development at less than 10 MAF in 60 percent of all years. DWR's key document on delta outflow, (CDWS 1978a) sums up San Francisco Bay's present outlook as follows:

> "In summary, there are yet no specific salinity or delta outflow requirements for the Bay complex west of Suisun Bay that apply to the operation of the SWP or CVP. This is not to say there will be no freshwater inflow to San Francisco Bay. Controlled delta outflow to protect designated beneficial uses in the delta and Suisun Marsh will constitute a major source of inflow to the San Francisco Bay. Moreover, substantial unregulated flows in excess of flows for designated uses will continue in all but the driest years. These flows are estimated to average 11.6 cubic kilometers (9.4 million acre-feet) per year under year 2000 conditions The SWRCB plans to adopt guidelines for their preservation pending determination of specific needs."

Thanks to 19 years of study by the water development, regulatory and fish and wildlife agencies, the delta's prospects are more in focus, described in Bulletin 76 (CDWS 1978a) as follows:

> "The overall net water requirements in the delta include internal consumptive uses and net delta outflow for controlling salinity to protect agricultural, municipal, industrial, and fish and wildlife uses. Under the recommended plan, water necessary to meet these requirements will vary from about 4.9 cubic kilometers (4 million acre-feet) in a critical year to about 8.3 cubic kilometers (6.7 million acre-feet) in a wet year. As an area of origin, the delta under California law has priority to available water to meet these needs before water is exported."

Through estimates of what's left in the river for the bay may vary, and the actual flows are not really known, there is no doubt about the trend. The trend has been down for 80 years and is still pointed down, resolutely. If only 30 percent of the bay's inflow from the Sacramento-San Joaquin remains today it is certain that this will be reduced more, to only 10 or 15 percent of that original normal weather year flow, by the year 2000.

SAVING THE BAY ONCE, TWICE, THRICE?

Not only did the bay continue to suffer inflow losses during the 1970's, it also witnessed no gains in the bay fill and shoreline control programs that brought BCDC its fame in 1969. San Francisco Bay was not included in the more rigorous requirements of Proposition 20, applied to the coast from 1973 to 1976, nor in the 1976 California Coastal Act. Conservationists of 1972 did not want to place the bay program in the hands of the voters in 1972, nor in the hands of the legislature in 1976.

BCDC continues today in its avuncular role: older and wiser but with only the same patchwork control program its advocates won from the legislature and Governor Reagan in 1969. Except for the addition of Suisun Marsh in 1977, and some disputed authority over Federal actions through the Federal Coastal Zone Management Act, it has not garnered any new authority to deal with applicants, local jurisdictions, Federal development agencies or other state agencies. The weakness of BCDC's shoreline and wetlands controls is, perhaps, its most striking contrast with the more modern and pervasive approach of the California Coastal Commissions.

In an analysis done in 1978, one of the authors concluded that BCDC has effective land use control over only 26.6 percent of the bay's shoreline. This figure includes the areas within the so called Designated Priority Use category of the approved 1969 plan. BCDC's permit control in the remaining 73.4 percent of the bay's shoreline computes as follows: Tidal Marsh and Undesignated shorelines shown in the plan, permit control over a 100-foot wide band but good only for requiring public access, 25 percent; Saltpond-Managed Wetlands, with permit control only covering the bay-facing first dike, 15.1 percent; "Certain Waterways," where control applies only to mean higher high water (MHHW) or to five feet above mean sea level (MSL), 33.3 percent. The study did not attempt to measure the shorelines of upstream portions of local tributaries, which are totally excluded from BCDC permit control, or the Suisun Marsh area added to BCDC's jurisdiction in September 1977 (Davoren 1978).

BAY POLLUTION CLEANUP

The only net gain for the bay in the 1970's, then, was cleaning up the Bay Area's municipal and industrial discharges into it. After rather ineffectual starts, in the 1950's with the SERL studies and the 1960's with the Kaiser Engineers Reports, the Federal, state and regional water quality control programs began having useful impacts in the 1970's. All Bay Area municipalities will have facilities capable of meeting current waste discharge requirements by 1986 (Eastman 1979).

However welcome this development, which got underway seriously only with passage of the Federal Clean Water Restoration Act of 1966, it must be seen as the result of applying national and state water quality improvement programs to the Bay Area rather than the result of a bay centered program rising from the endemic needs of the bay itself. But the results to date, and yet to come when the belated, massive City and County of San Francisco sewage construction program is resolved, provide a crucial advance in the process of requiring permanent, beneficial maintenance of San Francisco bay's values.

THE VIEW 40 YEARS BACK

Looking back over the 1970's, the 1960's, the 1950's, and the 1940's, it is sad to conclude that the Save the Bay effort of the Sixties remains the only deliberate attempt of the past 40 years (1) to understand the bay's ecological and systemic needs, at least partially, and (2) to devise ways and means to protect the bay for the intrinsic values the bay itself offers to present and future generations. Other than the BCDC experience, circa 1965 to 1969, altruism on the bay is dead and has been for a long time.

The driving force behind all other appraisals of the bay's biophysical limits, its hydraulic or chemical properties, or of its economic, social or legal values, can be traced directly to a project, a policy, an agency mission, or a public or private proposal to use, change or abuse the bay in some way.

The two newest studies of the bay, one that started in January 1980 and the other getting started this year or next, follow this well-established tradition. Both are required by the State Water Resources Control Board, both represent long overdue technical efforts, and both theoretically have the welfare of the bay as a major purpose. However, both are being paid for and nominally produced by the two basic classes of water users that most seriously impact the bay. These are: (1) the two major diverting agencies upstream, the Department of Water Resources and the Water and Power Resources Service; and (2) the 90 or so municipal and industrial dischargers to the bay.

The first is to determine how much water the two agencies can or should leave in the system to protect the bay's ecological needs, and its beneficial use entitlements if any, per Water Right Decision 1485 (CWRCB 1978a). The second is to determine the relationships between delta outflow and discharges to the bay, and vice versa. Obviously, both classes of bay users have a strong (A) metaphysical or value interest in keeping their obligations to the bay at a minimum. Definitive results from both studies, presumably, should be available in August 1986 when the State Board begins two years of hearings to determine if and how much delta outflow the bay is to receive as a matter of right. But, in both cases, the biophysical needs of the bay will likely be integrated into the decisionmaking functions of the water management agencies not as an objective but as a constraint on other (project) purposes.

Another current study with (A) metaphysical or value relationships to the bay is the $2 million Bay Area Water Reuse Study now sliding noiselessly from Phase One to Phase Two. This is an economic and engineering feasibility investigation, managed by CH2M Hill (1979), to determine if the now-cleaned-up water flowing to the bay from 31 municipal outfalls--530 million gallons per day--can be captured for some beneficial use somewhere else. There is also a Central Valley regional group tied into the study, interested in using the water there for irrigation instead of letting it flow, wastefully, into the bay. Potentially, about 500,000 acre-feet of reuse water is involved.

The benefits, if any, of leaving this water in the bay are not as easy to compute as crop yields in the valley, so this has not been analyzed. Using the reclaimed water for high-minded but low-pay purposes such as bayside marsh restoration has a hard time competing in the real world. However, another real world reality, rising energy costs, indicate the water may have to be left in the bay, or Bay Area, rather than being pumped elsewhere for some recognized beneficial use.

A NEW PLANNING PREMISE FOR THE BAY

In the authors' view, San Francisco Bay's destiny has been drifting for at least a decade and a new basis for determining the bay's future must be installed. In the context of earlier comments, the bay's scientific effort to date has been relatively competent on (C) procedural levels but has not addressed (B) theory sufficiently and has been totally deficient in the (A) value category. More specifically, a better targeting procedure for bay research would seem to require as a first premise more attention to the metaphysical basis underlying research efforts with respect to freshwater inflow. In the case of San Francisco Bay, for example, the alternative metaphysical premises could be:

1. It is desirable to divert and export as much water as we can out of the Sacramento-San Joaquin Bay-Delta system.
2. It is desirable to maintain the soundness of San Francisco Bay to support a variety of social, ecological and economic activities.
3. It is desirable to leave all remaining natural attributes of San Francisco Bay untouched and limit further man-generated impact upon them.

Each metaphysical premise will have a profound and differentiated impact on the way science proceeds in the bay. Alternatively, where metaphysical premise is lacking, or poorly defined, science's ship may find itself sailing in ever-tightening circles, or locked in irons with its sails askew.

The authors thus recommend a full treatment of San Francisco Bay by science, including its metaphysical aspect. Acceptance of metaphysics, or human value, as a basic ingredient of scientific procedure in bays has an immediate secondary implication for implementive strategy:

> By systemic treatment of impact sources as well as effects, it facilitates re-emphasis of research from description to prediction goals.

Some level of description is of course, necessary for prediction. But the nature of research conducted will be quite different depending on what level of importance is assigned to each of these two goals. In the case of the bay-edlta, certainly more is needed than the numerology that has comforted the technicians on one hand and the politicians on the other in the past--such as the delta Outflow Index, the Striped Bass Index, Relative Toxicity, and Species Diversity.

Because scientific procedures take time--usually measured in years or decades--it is essential that they deal as much as possible with future requirements rather than past events. The widening gap between knowledge about environmental systems and the rate of man/technology impacts upon those systems has been demonstrated by Bella (1974). In San Francisco Bay's case it seems more critical to know what impacts will and will not be felt by the bay over the next 5 or 15 years than what has happened to it over the past 100 years. Yet such a targeting mechanism does not exist, or is left to an essentially adversary contest between interest advocates and/or their associated agencies. A cohesive futures planning mechanism, that focuses not on particular interests but on the continuing capability of the bay to service both ecology and man, would seem an important step in that direction. A scientific perspective that can systematically deal at a theoretic level with known and unknowns, and that can both describe and predict, will be required. Time is not available here to describe the constructs of such theory, described elsewhere by one of the authors (Meyer 1980a,b), and others (Bella 1974, Neurath 1973, Haskell 1896). Development should not be expensive, but will require two ingredients familiar to science--hard work and continuity of effort.

The Fish and Wildlife Service has devloped one approach for a Bay Institute to sponsor and perform the bay-centered research and development functions described here (Davoren and Meyer 1980).

Science and scientists have an impressive and expanding record of increasing knowledge of bay systems. Evaluated on that track alone, they seem as well conditioned as our best Olympic athletes. But if determined to run the uncertain and even more demanding course toward future decisions affecting San Francisco Bay, they will need not only their conditioning but a sense of direction and a better map. Neither is very expensive, but both will require new and continuing effort. Failure to provide such tools, on the other hand, offers a real potential for misjudging the finish line--or, even more likely, being unable to find the starting line.

DISCUSSION

Question: Dick Baily, Department of Housing and Urban Development: How are you going to document the metaphysical needs?

Answer: Well, why don't you pick up something I haven't laid out, but I'll be glad to give it to you. It's called discussion paper Number Two. It's on the nuts and bolts of how we would intend the institute to function. We would have two bay forums and a development program going on. And once we get the problem well identified with the need to document metaphysical and other values, we think the process would begin taking on a momentum of its own, derived from all the interested sectors of the bay. The techniques for doing that are more my partner's category than mine. See his publications for details (Meyer 1978, 1980a, 1980b).

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CHAPTER 13

FUNDAMENTAL FACTORS INFLUENCING FRESHWATER INFLOW TO ESTUARIES

THE RIVER CONTINUUM: A THEORETICAL CONSTRUCT FOR ANALYSIS OF RIVER ECOSYSTEMS

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ABSTRACT

The river continuum concept suggests that a natural river system, from headwaters to estuary, can be considered a gradient of process zones ranging from a strongly detrital-based system in headwater streams to a seasonal, or perhaps annual, autotrophic regime in moderate-sized streams and then, a gradual return to predominately heterotrophic processes in large river systems. The structural and functional properties of stream communities tend to be selected to conform to the dynamic patterns of physical energy expenditure and the most probable physical state as proposed by fluvial geomorphologists. Each stream reach along the continuum has local inputs in the form of light energy and particulate material from the terrestrial landscape and the partially processed materials transported from upstream reaches. Particle size of organic material in transport becomes progressively smaller as it passes down the continuum and biotic communities structured on the transport system become progressively more efficient in processing smaller particles towards downstream areas. Consumer communities in rivers are considered to be structured by (1) local inputs, autochthonous and allochthous; (2) materials in the transport system and (3) gradients in fluvial geomorphic processes throughout the drainage network.

INTRODUCTION

The objective of this paper is to provided review and elaboration of the River Continuum Concept (Vannote et al. 1980). This concept suggests a theoretical construct for a natural river drainage system for identifying and interpreting: (1) natural gradients in the quantity and quality of organic inputs to reaches along the river ecosystem; (2) strategic patterns evolved by consumer assemblages for processing organic energy available to the river system; and (3) process efficiencies associated with the utilization of energy inputs throughout the continuum.

The river continuum concept suggests that structural and functional characteristics of biotic communities are uniquely adjusted and largely regulated by gradients in fluvial geomorphic processes. The physical processes are determinates of channel geometry and define the rate of kinetic energy expenditure per unit of channel length.

REGULATION BY THE PHYSICAL AND GEOLOGICAL SYSTEM

As streams flow down mountain slopes, across valley floors, and subsequently to estuaries and the ocean, great amounts of potential energy are dissipated in turbulence along the bed of stream, against stream banks, and in falls and rapids. Energy is also dissipated in the transport of sediment and debris. Geomorphic concepts, progressively developed and reported by Leopold and Maddock (1953), Leopold and Langbein (1962), Langbein and Leopold (1966), and Scheidegger and Langbein (1966) theorize that stream systems tend toward an equilibrium condition by achieving a balance between the rate and uniformity of energy expenditure throughout the stream channel. This balance in the use of energy is achieved by internal adjustments in channel geometry that include such factors as width, depth, slope, sediment transport, bed shear, and friction.

MOST PROBABLE STATE

The theory that river systems tend to achieve an equilibrium condition led to the idea that streams proceed toward a most probable physical state throughout the drainage network (Chorley 1962). Thus, the river network is viewed as representing an efficient form for transporting variable quantities of water and sediment. A change in the rate of sediment or water input is rapidly accommodated by adjustments in hydraulic properties so as to minimize the change in channel geometry (Leopold and Maddock 1953).

The river continuum hypothesis suggests that biotic communities that develop in river reaches may simultaneously achieve a most probable state with respect to their structure and function, analogous to the "most probable" concept for fluvial processes of the physical system. Both the structural and functional properties of biological communities are viewed to shift rapidly and in parallel with changes in the way the physical system spatially or temporally redistributes its use of energy. These biological changes may be observed to occur gradually along the river channel as the drainage basin enlarges, but may also occur in localized areas following watershed disturbance and resultant alteration of energy and nutrient inputs.

To examine and interpret spatial shifts in the distribution of kinetic energy of flowing water systems, basic organic energy inputs, and resultant gradients of communities through river networks, a stream classification model used by fluvial geomorphologists is adapted. In this discussion, the stream order classification originally developed by Horton (1945) and subsequently modified by Strahler (1957) has been used. Within a given physiographic province or division, stream order is related with considerable precision to the number of tributaries of given stream order, channel length, watershed area, and discharge (Leopold et al. 1964; Shreve 1966; Flint 1974).

LANDSCAPE INTERACTIONS

Energy and material budgets of small upland tributaries are profoundly regulated by terrestrial systems. Low order streams are highly dispersed through watersheds and collect, process, and convey products shed from the landscape. Structural and dynamic properties of headwater reaches are highly sensitive to change, responding almost immediately to altered inputs of light, sediment, nutrients, and changes in runoff rates. Vegetative shields on terrestrial landscapes are critical in regulating the supply of sediments, nutrients and water to the channel (Likens and Bormann 1974; Vitousek and Reiners 1975). Evaluated on the basis of stream length, first- and second-order streams collectively exceed 75 percent of the total length of U.S. streams (Figure 1) and function as a critically important link in the continuum as sources of nutrients and organic material to larger streams.

THE NATURAL RIVER SYSTEM AS A CONTINUUM

Natural stream ecosystems are comprised of assemblages of organisms that are structured through an orderly process of successional phases of community development. They have achieved a homeostasis of structure and function within the limits imposed by the physical system (Odum 1969). The stream system, with its hierarchy of drainage networks is a highly open system receiving substantial inputs of reduced carbon compounds (soluble and particulate) produced in terrestrial systems. Small, low-order streams that flow through forested watersheds are dominated by the processes and efficiencies of biological and geochemical cycles of the forest. River process zones and the structure of communities in stream systems shift spatially in response to the degree that terrestrial vegetation affects inputs of light and particulate organic matter.

Stream ecosystems form a continuum from headwater tributaries t downstream rivers and estuaries. Both dendritic and trellis river systems can be considered a continuum of process zones, and the attendant communities can be characterized by gradients in the qualitative properties of organic inputs along the system. Principal biological process zones of a natural river continuum are shown in Figure 1 as a schematic overview. Extending from headwaters to the mouth, this hypothetical drainage system includes twelve stream orders, indicated on the diagram as an geometrically decreasing scale in order to reflect the disproportionately large number of smaller streams. Superimposed on this stream gradient are principal process zones characterizing relative degrees of heterotrophy and autotrophy along the continuum. Width of process zones is approximately proportional to the amount of organic energy provided at that point on the continuum.

Along headwater tributaries and low-order valley streams (orders 1-3), channel widths are sufficiently narrow to permit a closed forest canopy. The interception of sunlight limits autochthonous production (e.g., about 0.2 percent of the organic budget of Bear Brook; Fisher and Likens 1972, 1973) with the result that forest-dominated stream systems are strongly heterotrophic. In excess of 75 percent of the energy base of low-order streams is commonly derived from terrestrially produced organic matter, including tree limbs, twigs, leaves and needles, and soluble organics. The importance of large particulate detritus to stream function has been widely demonstrated (Minshall 1967, Hynes 1970, Kaushik and Hynes 1971; MacKay and Kalff 1973, Sedell et al. 1974, Cummins 1974, among others).

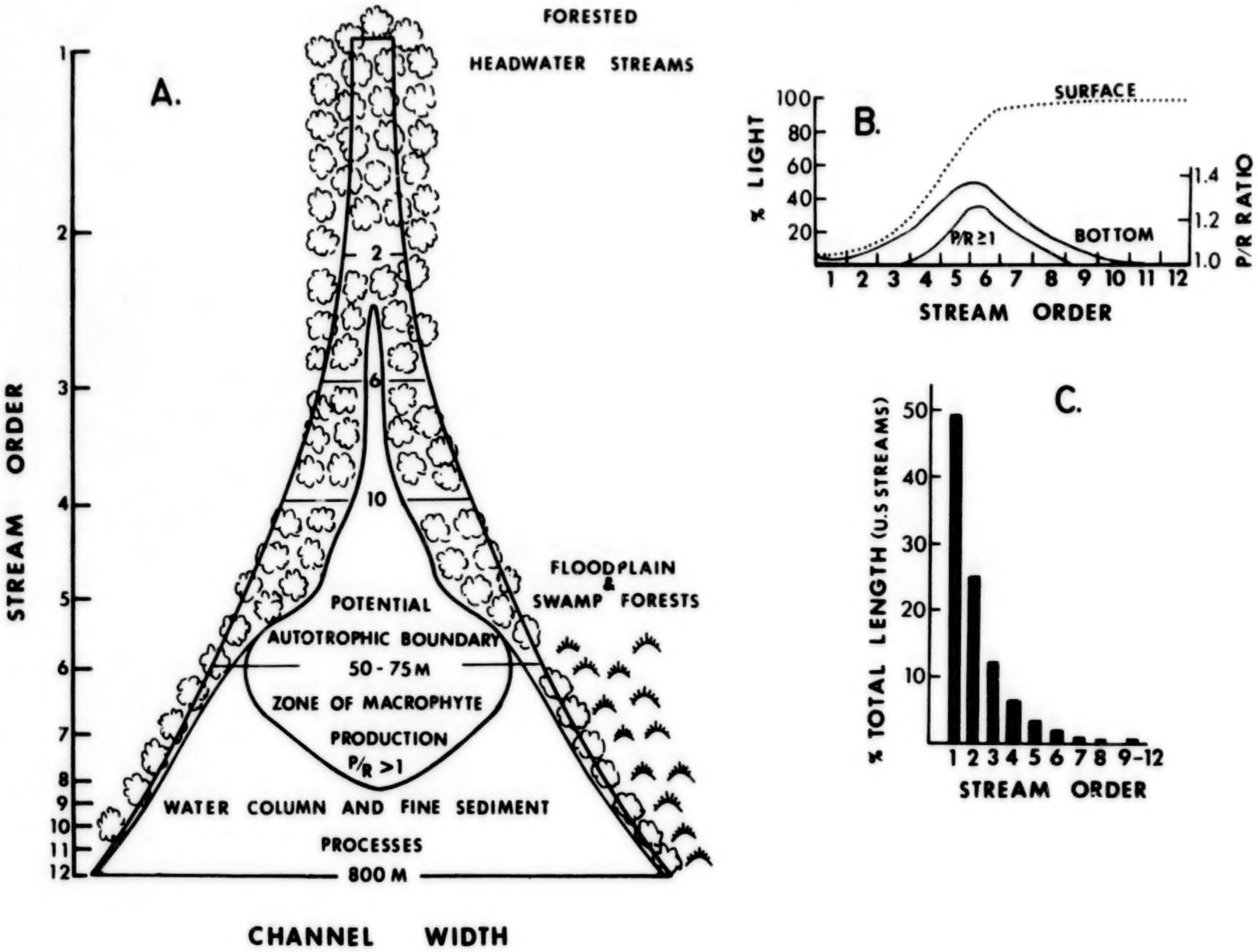

Figure 1. (A) Schematic overview of a hypothetical river drainage system located in a mesic deciduous forest region showing gradations of principal process zones from the forested headwater tributaries to intermediate autotrophic zones and the fine particle sediment and water column process zones in the large river system. Stream order is indicated on a ratio scale. River width (meters) is proportional to stream order. (B) Trajectories of percent incident light reaching the stream surface and the substrate level along the river continuum. The river reaches where autotrophic processes may dominate (P/R >1) is estimated as a function of decreased canopy shading and silt-transport in downstream high order rivers. (C) The estimated percent of total length of streams of various orders in the contiguous United States.

Autotrophic processes gradually increase toward mid-order (4-8) stream reaches since as tributaries unite, channels widen the gradual separation of the forest canopy permits an increased input of solar energy. In response, autotrophic processes become progressively more important in sustaining energy flow, and the role of local detritus input diminishes. Mid-order streams (orders 3-6) may develop autotrophic zones, where, at least seasonally, the gross photosynthesis may exceed community respiration ($P_g/R_c > 1$). Along natural river courses, with intact riparian vegetation, autotrophic zones are confined to reaches where stream width exceeds about 10 m, although upstream extension (Minshall 1978) may occur seasonally; for example, prior to leaf formation and after autumn leaf fall.

Mid-order segments of the continuum encompass stream sites having the greatest potential for production of rooted aquatic macrophytes (Figure 1). Macrophyte production (e.g. Elodea, Vallisneria, Potamogeton) represents a form of temporary storage because of limited consumer grazing. During autumn die off, many species of aquatic macrophytes are rapidly decomposed by microbial invasion and disintegrate into fine particulate detritus. This autochtonous source of fine particulate material may provide an important food base for both mid-sized and large rivers. Organisms adapted to process coarse particulate material (invertebrate shredders) are generally rare or absent in midorder streams, presumably because of diminished inputs and retention capacity of larger streams. Failure to adapt to thermal patterns characteristic of mid- and large-order streams may also be a factor contributing to reduced shredder activity.

On large rivers (orders 9 to 12) there is tendency for the system to return to predominantly heterotrophic processes (Figure 1). Benthic photosynthesis is often greatly reduced due to increased water depth and turbidity reducing the amount of light reaching the stream bottom. As a result, large rivers may return to a heterotrophic status and become strongly dependent upon transport of the algae and fine particulate materials produced and partially processed by upstream communities. Dominant biologic processes are associated with the water column, and fine organic particles in sediments (Mann 1972). Fine particulates in sediment and transport are considered a major energy base for the large river community.

Flood plains and swamp hardwood forest bordering large rivers are postulated to provide an important subsidy of partially processed fine particulate detritus. This flocculent material generated from forest debris may be captured by rivers during the annual flood and withdrawn into the channel by return flows. Large-order streams frequently are low gradient, have broad low-relief flood plains, and are commonly bordered by swamp or bottomland forest that are inundated by annual floods. During inundations, coarse particulate organic materials, sand and silt are entrained; during recessional stages, return flows may carry substantial energy subsidies consisting of soluble and fine particulate organic material. The flocculent fine particulate matter has a low specific gravity and is highly prone to suspension. Major contributions to rivers may be associated with localized or regional storms that purge the bottomlands but are not of sufficient geographic extent to elevate river stage. Rivers transversing extant coastal plains and delta areas, often inundate bottomlands for extended periods thus allowing direct biotic interexchanges with the swamp forest ecosystem.

CONTINUUM OF ORGANIC INPUTS

Estimates of particulate organic-matter inputs along the continuum of a twelfth-order drainage system are partitioned into most probable sources (Figure 2). Trends projected beyond fifth-order streams are based on limited data and theoretical projections because few studies of this nature have been made on large rivers (Mann 1975). It is questionable, however, whether a sufficiently natural stream exists for obtaining measurements on a drainage larger than fifth- or sixth-order outside certain tropic and arctic regions. Input parameters for Figure 2 are based upon a total particulate matter input of about 1000 $g/m^2/yr$ to low-order streams, progressively decreasing to about 600 $g/m^2/yr$ in reaches along high-order streams. The five principal inputs include: coarse particulate organic matter, periphyton production, rooted macrophytes, phytoplankton production, and the fine particulate organic matter imported to rivers following flood inundation of riparian ecosystems. The ratio of these components gradually shifts as the relative inputs increase or decrease along gradients comprising the river continuum. The distribution of functional groups of organisms in the continuum is, in part, regulated by the continual adjustment to these inputs.

The five particulate categories are plotted to show the expected input potential for stream orders of the drainage network. Rates of organic loading will vary significantly along the continuum for each input parameter, and for regional drainage basins, trajectory estimates are feasible to predict the most probable state. Input rates for various river segments are largely determined by the physical system and degree of control by riparian vegetation.

In contrast to decreasing energy loading with increasing drainage area (Figure 2), a concept of equal energy availability throughout a regional drainage should not be considered as unrealistic. Highly open systems are greatly subsidized by surrounding landscapes and yet, in most reaches, can maintain autochthonous processes. Additionally, the transport of organic matter by flowing water may be an important mechanism for equalizing the distribution of energy among stream orders.

Transport System

The continuum is predicated upon the functioning of the transport system. This system is maintained by flowing water and the supply of particulate organic material from both upstream and riparian landscapes. The river transport system, both during low flow and flood flow, is considered an important energy subsidy for equalizing energy loading and redistributing various size fractions of organic matter throughout the continuum. Storm flow transport may lead to increased efficiency in biotic processing by suspending, sorting, and re-depositing particulate organic material and organic solutes sorbed onto silt and clay particles to more permanent retention sites associated with alcoves, pools and sloughs along the river course.

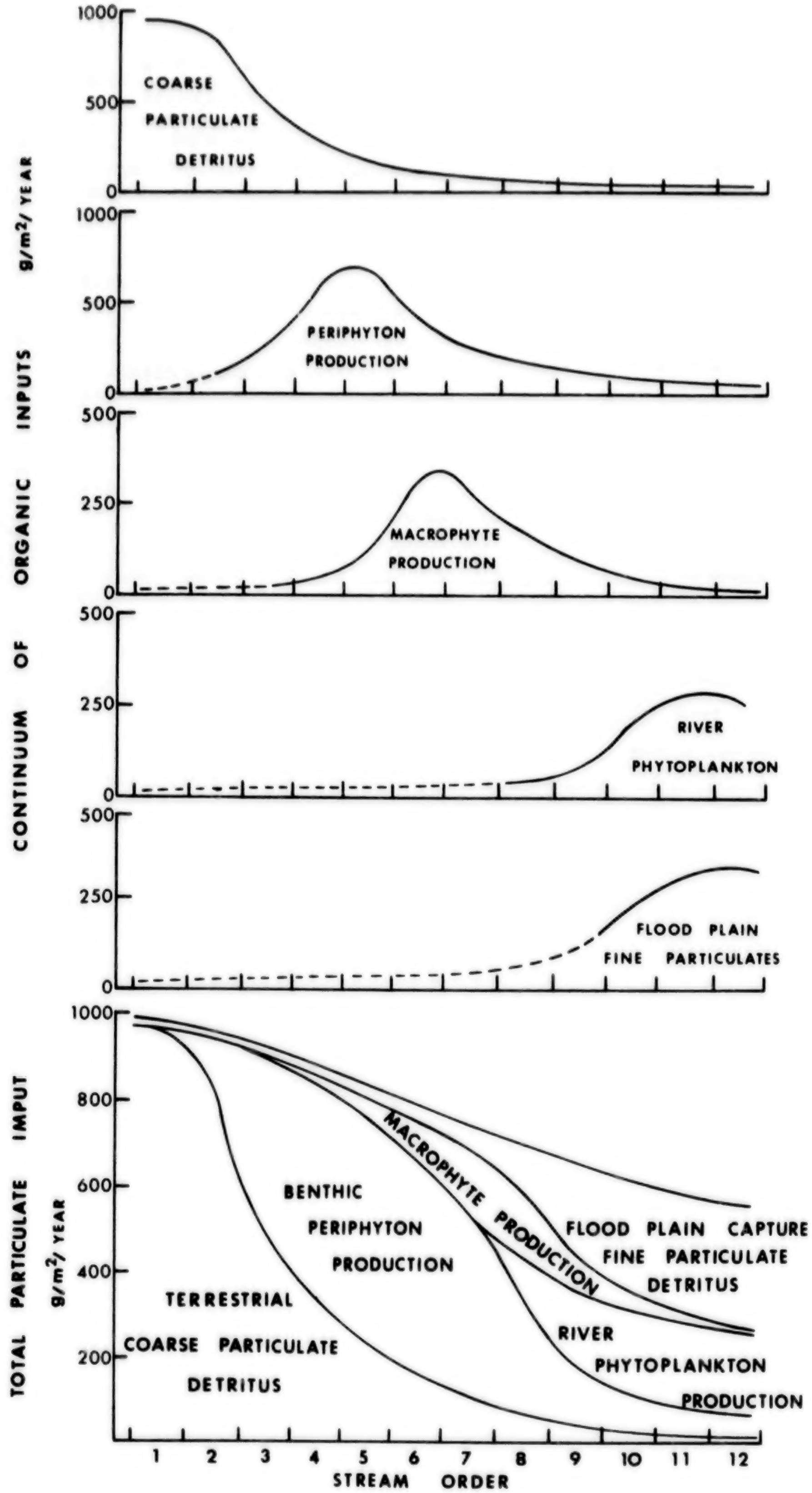

Figure 2. An estimated projection of the most probable theoretical distribution of organic inputs from within stream autotrophic processes and terrestrial sources along a twelth-order continuum.

Functional Groups

The relative dominance of invertebrate functional groups (Cummins 1974) shifts spatially (Figure 3) in parallel with the qualitative changes in particulate organic inputs and primary production along the continuum (Figure 2). Headwaters are characterized by high-shredder and low-grazer densities relative to middle-sized rivers in which increased densities of periphyton grazers, fine particulate collectors, and benthic filter feeders are coupled to greater plant biomass and fluxes of fine particulate organic matter. In large rivers, the dominance by sediment burrowers and water column filter feeders (planktonic crustaceans) is coincident with increased amounts of fine particulates in sediment and transport.

Diversity and Stability

Gradients in the functional composition of consumer assemblages established within specific reaches of the continuum are hypothesized to be structured primarily on: (1) rate and variance of physical energy expenditure, (2) particle size distribution of local organic input and the ratio of the terrestrial input to autothchonous production (primarily algae), and (3) the qualitative properties of organic matter in transport.

Diversity of consumer organisms in the river network probably shifts in direct proportion to the variance of the physical system and heterogenity in the particle size composition of the food supply. River segments that exhibit low or minimum variance for the trophic and physical (temperature, substrate, gradient) systems are apt to have low biotic diversity.

This idea of system stability as a dynamic balance is shown in Figure 4 characterizing a single stabilizing vector, species diversity, and an instability vector represented by thermal noise (maximum variance in diel temperature). In stream zones characterized by a high Tmax, stability is achieved by a high biotic diversity; whereas in stream zones displaying a low temperature variance, stability may be gained at a low species diversity. In reality, there are likely to be many identifiable vectors contributing to the stability or instability of the system and the strategy might be better exhibited by an array of vectors contributing in varying degrees to the stability of the total system.

In this interpretation, system stability is achieved by a dynamic balance between those vectors contributing to stabilize the system and vectors contributing to the instability of the system. In systems with a highly stable physical structure, biotic diversity may be low and yet preserve the total stability of the landscape or stream system. In contrast, physical systems with low resistance to physical variations may require a high species diversity or at least a high complexity in species function to maintain stability. Consumer diversity is predicted to reach a maximum in third- to fifth-order streams in parallel with higher diversity of particulate inputs, high diel and annual thermal variances, and increased physical heterogeneity. A projected trend towards reduced diversity in larger river systems can be attributed to: (1) the reduction in river competence that directly leads to a more uniform distribution of fine substrates, (2) a predominance of uniformly fine organic material in both the transport system and in the sand-silt sediments, and (3) a great reduction in diel temperature variance.

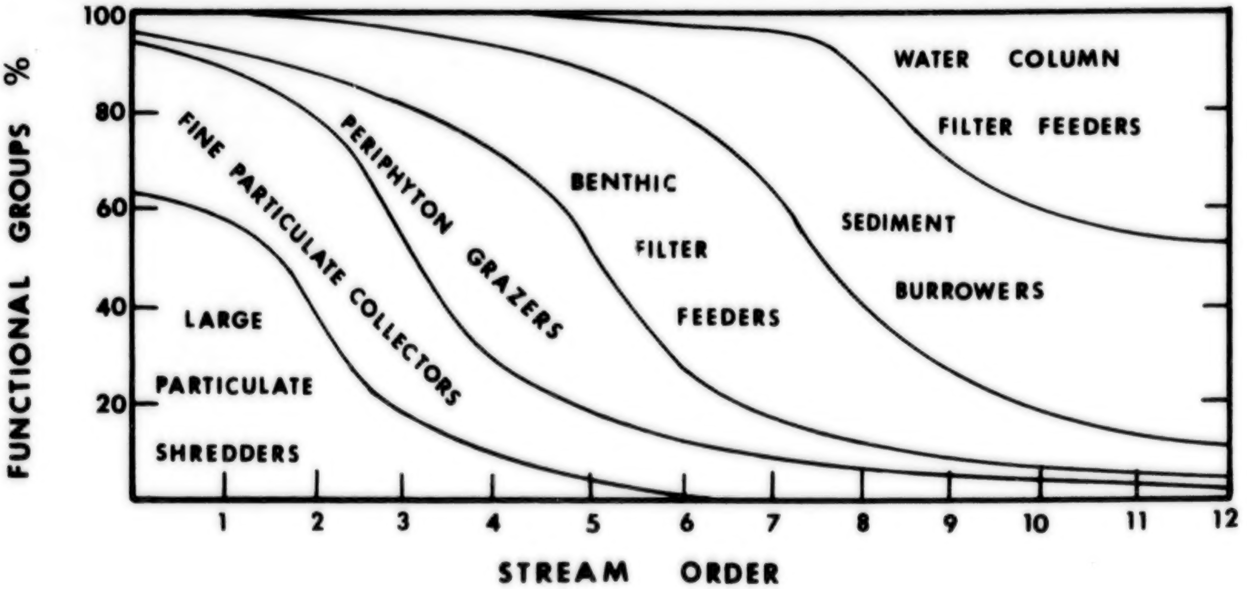

Figure 3. Estimated trajectory of functional groups of consumer organisms extending through a river continuum from headwater spring seeps to a twelfth-order river in a humid temperate region.

Spatial and Temporal Processing of Organic Inputs

Energy fluxes available to consumer organisms range from the sudden, random, inputs of dissolved organic compounds to the highly predictable, seasonal import of energy made available by entrainment of forest litter and stream autotrophs. In undisturbed river systems, pulsed energy input is accommodated and rapidly dampened by the fast response time of microbes, temporal sequencing of consumer organisms, partial processing within each reach, temporary local storage, and transport to intermediate points along the continuum. Both the feeding strategies of various invertebrate functional groups and the degree of particle size specialization (Wallace et al. 1977) are adjusted to a specific periodicity of loading events and constraints imposed by the physical dynamics of river systems.

Recent studies of biotic processes in White Clay Creek provide evidence that the ecological stategy for natural streams may be a propensity toward an equilibrium of energy flow through biological communities on an annual basis. Although processing rates and efficiency of energy utilization by consumer organisms appear to approach an equilibrium, their food resources shift seasonally. Seasonal inputs of leaf litter are utilized throughout a progressive reduction in particle size. This initially involves shredder groups, but gradually shifts throughout the continuum to communities dominated by collectors, filter-feeders, and sediment burrowers.

Studies on White Clay Creek basin (Vannote 1978; Sweeney and Vannote 1978; Vannote and Sweeney 1980) have shown that in natural stream systems biotic communities in stream systems biotic communities in most habitats can be characterized as having a continuum of synchronized species replacement. As a consumer species completes growth in a particular microhabitat, it is immediately replaced by another species performing essentially the same function, differing principally by the season of activity. It is this continuous species replacement, coupled with resource partitioning (food substrate and physical habitat) that leads to distribute the use of organic matter over time. Thus, it is theorized that components of biological systems evolve toward an equilibrium of energy processing by maintenance of a central position between a tendency to make maximum use of available energy inputs (maximum efficiency) and an opposing tendency to use energy at a uniform rate throughout the year (minimum variance; Figure 5).

Extrapolating from these strategic process patterns observed for consumer organisms in low-order (1-4) streams (Vannote 1978; Vannote and Sweeney 1980), it is theorized that the organization of natural communities throughout the continuum may have similar process strategies directed toward maximizing utilization of available energy. Since shifts in hydraulic geometry of the physical system assume different but statistically predictable patterns of energy expenditure and work characteristics along the continuum (Scheidegger and Langbein 1966) and, available nutrient inputs to an unperturbed system appear to vary predictably, the processing characteristics of communities are predicted to shift in parallel and attain a most probable state (structure and function) along river gradients. Furthermore, it is assumed that communities characteristic of each stream reach are assembled through

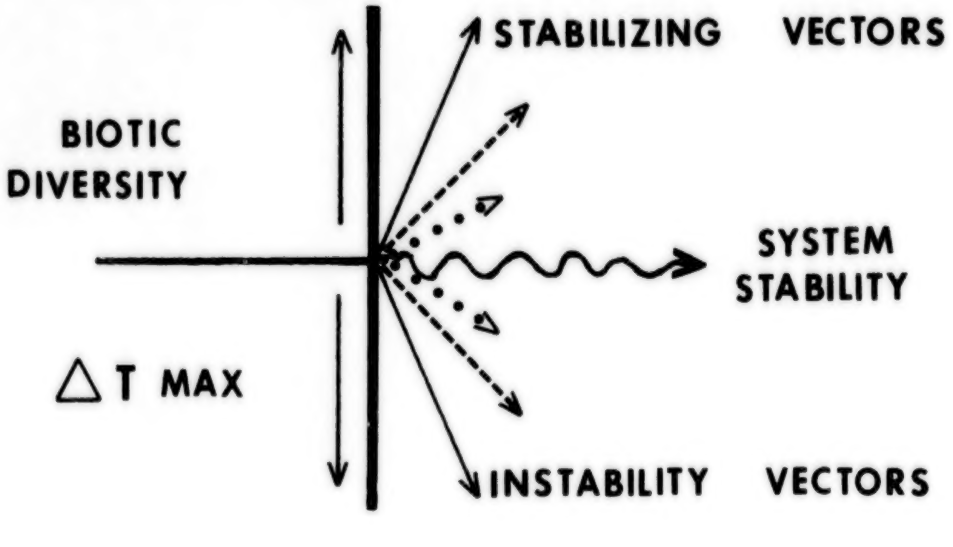

Figure 4. A diagram illustrating how ecosystem stability may be achieved as a dynamic balance between vectors contributing to stabilize the system and vectors leading to instability (see Vannote et al. 1980, Vannote and Sweeney 1980). Example uses only a single instability factor, maximum diel temperature pulse (ΔT_{max}).

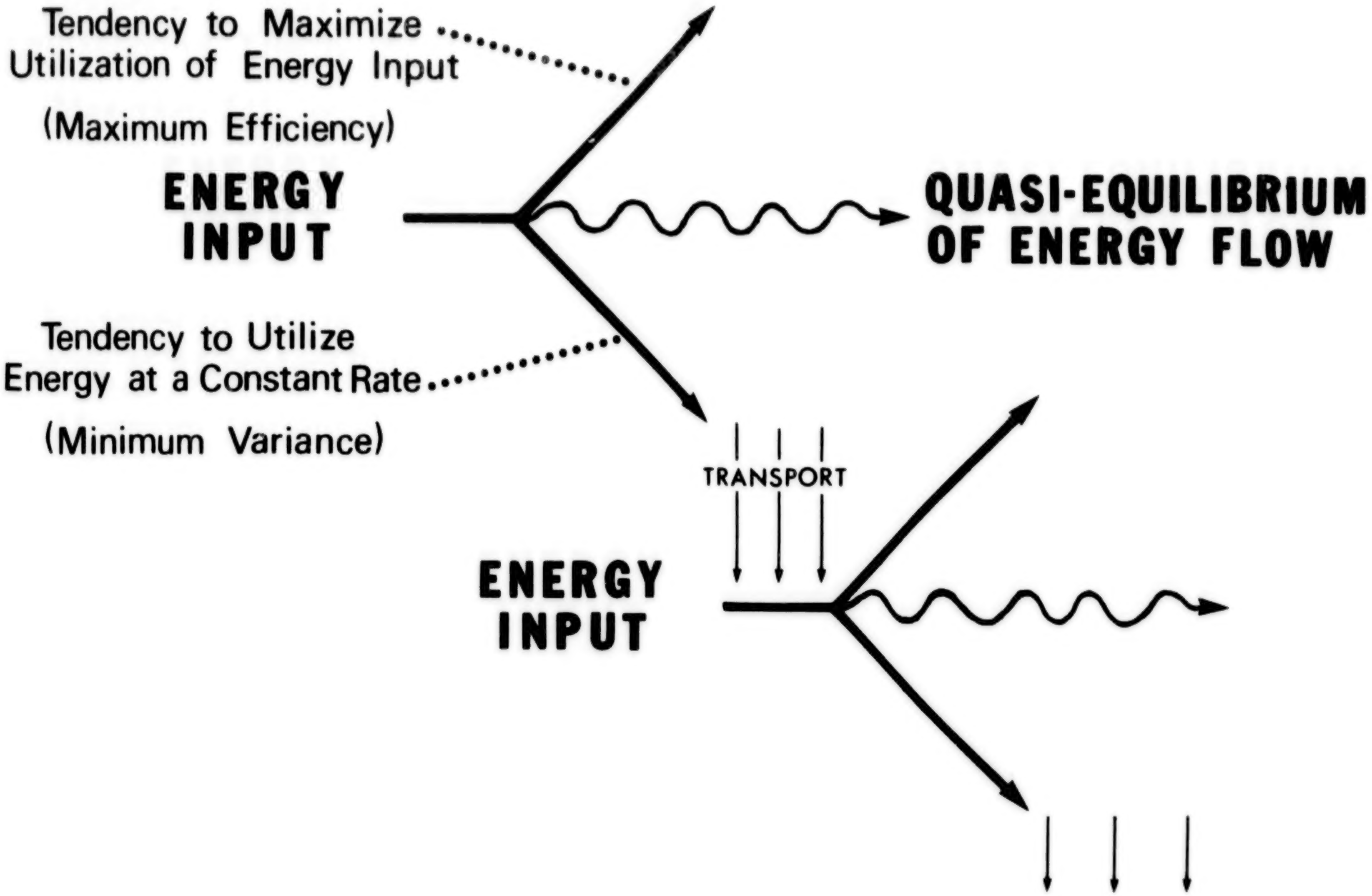
Tendency to Maximize Utilization of Energy Input
(Maximum Efficiency)
ENERGY INPUT
QUASI-EQUILIBRIUM OF ENERGY FLOW
Tendency to Utilize Energy at a Constant Rate
(Minimum Variance)
TRANSPORT
ENERGY INPUT

Figure 5. A model for two adjacent stream reaches representing possible compromise between biotic tendencies to maximize the use of energy taken into the system and an opposing tendency toward utilizing energy resources at a constant rate. The balance is a quasi-equilibrium of energy flow through consumer organisms representing a compromise in efficiency and leads to transport of energy to downstream communities.

ecological development (Odum 1969) to minimize energy losses and to process energy as equitably as possible on an annual basis.

A model representing two adjacent stream reaches along a continuum is conceptualized in Figure 5 and represents the idea of an ecosystem compromised between a tendency for biological communities to maximize the use of available energy (imported detritus and autotrophic stream production) and an opposing tendency to utilize available energy at a rather constant rate. The most probable central position between the two opposing strategic tendencies leads to a quasi-equilibrium of energy flow through consumer assemblages. Incomplete utilization establishes a partial but predictable export of resources largely during randomly occurring storm events.

A quasi-equilibrium state is attributed to continual seasonal adjustment of community structure to predictable seasonal changes of input variables. These changes may include seasonal terrestrial inputs of detritus and algal production, pulsed inputs of soluble organics, and a constant transport of organic particulates to downstream reaches.

Transport from upstream reaches, coupled with local inputs, comprise the energy input (Figure 5) to downstream systems. Downstream communities are structured, in part, on the average, most probable performance efficiencies of upstream communities. Based upon patterns of fish and invertebrate feeding behavior, both upstream inefficiency and downstream community adjustments seem to be predictable throughout a drainage network. Adjustment may be characterized, for example, by progressive shifts toward filter-feeding arthropods and mollusks in middle-order streams (5-7), yielding to a dominance of water column grazing by microcrustaceans and sediment burrowing consumers in larger rivers.

A tendency towards temporally uniform rates of activity by many internally linked functional groups (Vannote and Sweeney 1980) that are active during all seasons of the year contributes to the ecosystem being directed towards a quasi-equilibrium of energy flow. The above referenced examples represent only a portion of the complex nature of community development that has evolved in natural river systems. Species components shift spatially (Ross 1963) and the high diversity of insects found in mid- and low-order streams is gradually supplanted by mollusks, fish, crustaceans, and annelids, among other groups, in higher order rivers.

RESEARCH AND MANAGEMENT IMPLICATIONS

Major segments of this Nation's large rivers, such as the Mississippi, Ohio, Missouri, Arkansas, Tennessee, and Columbia, are essentially a chain of lakes or ship channels. The Mississippi River, because of navigation works and levee construction, is not in physical equilibrium, and the natural dynamic regime, established since the end of the Pleistocene Ice Age, has been eliminated (Belt 1975). Biological populations and perhaps communities evolved in streams that were essentially in equilibrium and which had a heritage of sediment transport, cataclysmic flow events, thermal gradients, and a most probable geomorphic state. Channel modification often involved large changes in both channel geometry (local energy slope, cross sectional profile, modes of kinetic energy dissipation, riffle-pool frequency and meander patterns) and factors that regulate the spatial distribution, retention, and quality of organic inputs. These impacts reduce biotic efficiency and ecosystem stability and lead to diminished productivity and pulsed use of resources. Major problems often associated with channel modification are: (1) entrainment of unconsolidated sediments, (2) conversion toward laminar flow, (3) introduction of large thermal variances, and (4) disruption of the basic properties of organic inputs and retention.

Federal assistance programs have contributed to impoundment of numerous headwater streams for drainage, flood control, water supply, and irrigation. Headwater and large river impoundments not only alter downstream thermal regimes but are sinks for organic inputs. In addition, impoundments may eliminate flood flows and partially sever or alter essential energy linkage (accessability to bottomlands) for sustaining downstream communities. Regulation of flood flows, water diversion and low flow allotments often provide inadequate volumes to distribute materials along the continuum and may disrupt seasonal thermal patterns essential for maintaining community process efficiencies.

A management requirement is to determine the number and distribution of headwater streams that may be impounded without significant compromise to natural processes in master streams. A similar logic exists for evaluating the proportion of small watersheds that can be logged during a given rotation on drainage systems of various sizes. Clear cutting can cause local and translatory changes in nutrient flow, sediment yields, channel geometry, light and temperature patterns, and timing of snow melt, among others.

Treatment plants for organic wastes (domestic, cannery, etc.) are frequently sited along fourth-order and larger streams because small streams frequently have insufficient flows to accomodate effluents. Ironically, these river sites coincide with river zones of maximum autotrophic potential, and the nutrient enrichment invariably shifts natural equilibria. Furthermore, streams have small autotrophic biomass with high turnover rates and have considerably less capacity to retain inorganic nutrients than large biomass systems, such as forests where the total energy flow is great and nutrient cycles tend to be closed and circular.

River management must focus on the analysis of interactions between the river continuum and the natural and manipulated terrestrial ecosystems. Physical properties of rivers structure habitats and in combination with the vegetative shield of landscapes largely regulate the quality and fate of organic inputs. These factors then regulate community structure and function along the continuum. Perturbations cited above are only a few of the ways the continuum analysis is useful for management of river courses, predicting exports to estuaries, and recognizing temporal and spatial limitations of altered inputs.

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FRESHWATER INFLOW TO ESTUARIES,
SHORT AND LONG TERM PERSPECTIVES

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ABSTRACT

Evidence, from fauna buried beneath the upper Chesapeake Bay and from the presence of Crassostrea shell middens upstream from the low salinity limit of oysters, demonstrates that salinity in the estuary has been higher than it is at present. This is not consistent with a uniform rising sea level-rising estuarine salinity model. Changing land use in the upstream basins of both the Susquehanna and Delaware Rivers can be shown to produce significant modifications in peak and low freshwater discharges. At the present time, we cannot identify the cause of this salinity excursion in the upper estuary. Implications of land use, climate change, and competing demands for fresh water are discussed.

INTRODUCTION

Stimulated by the recognition that the carbon dioxide concentration in the atmosphere is increasing and that fluorocarbons can modify the upper atmosphere, much interest has developed about past, present, and future climates. As background to this conference on freshwater flow to estuaries, I will examine what we know about past and present freshwater discharge to several estuaries.

We have a tendency to think that the way things are is the way that they've always been. The geological perspective suggests that this is not the case at all. We need only go back ten thousand years to find convincing evidence of glaciers covering extensive areas of North America, with sea level 100 m below present, and the Atlantic coast of the United States located 100 to 150 km seaward of its present position. The present location of a city like Baltimore, Maryland, would be well inland and probably much colder than at present. There appear to have been perhaps 10 such ice ages during the last 5 million years. The history of past climates has been reconstructed well enough for us to apply statistical tests to the record. Random fluctuations are superimposed on periodic changes having frequencies of 100 to 100,000 years (NAS 1975) and some shorter-term solar cycles (King 1975). Four climatic epochs have been identified since the end of the most recent glaciation. These are the Altithermal (or warmest times) about 5,000 BP to 7,000 BP; the cooler Iron Age 2,900 BP to 2,300 BP; the secondary Altithermal of the early Middle Ages, 1,000 BP to 800 BP; and the Little Ice Age, about 550 BP. We are able to interpret climate almost solely on the basis of past temperatures. Data on rainfall are almost non-existent.

Man has measurably modified the climate on a local scale. Table 1 illustrates urban climate parameters as a function of rural conditions, demonstrating some startling differences. Extensive irrigation, drainage of large swamps and deforestation may cause significant local and regional climate changes.

With the background that the climate may vary significantly on both spatial and temporal frames, I will examine the freshwater discharge from several mid-Atlantic basins to their estuaries. My concept of the long-term (thousands of years) change in salinity, at a specified location within an estuary on the coast of the United States, is guided by the secular rise in sea level which has been occurring for the last 10,000 years. Our models indicate that this sea level rise has flooded river valleys, produced estuarine conditions, and that, at a given location within an estuary, conditions have become more salty up to the present maximum, provided that sedimentation rate is less than sea level rise.

RESULTS AND DISCUSSION

PRECIPITATION AND STREAM FLOW

The precipitation that reaches the ground within a particular region leaves as stream flow, evaporation and transpiration, or by out-of-basin diversions to other regions. On a basin-wide scale, stream flow is derived from the precipitation that falls within the basin boundaries and is divided into two parts: (1) direct runoff is water that reaches stream channels quickly after a period of precipitation or snow melt; and (2) base flow is water that reaches the stream much later as groundwater discharge from aquifers.

Precipitation that reaches the ground may infiltrate into the soil, run off the ground surface, or be evaporated into the atmosphere. The soil surface can absorb water at a maximum rate known as the infiltration capacity. If rainfall intensity exceeds soil infiltration capacity, the excess rainwater accumulates on the surface, fills small depressions and flows downslope as overland flow. Land surface characteristics such as vegetation and soil condition are the major factors that determine infiltration capacity. Coarse textured soils have a higher infiltration capacity than do clayey soils. Dense vegetation protects the soil from the direct impact of raindrops, provides organic matter to the soil and promotes biological activity in the soil to form open, stable, soil aggregations. Depending on the hillslope, overland flow travels at velocities of 10 to 500 m/hr. Thus, overland flow can contribute water to streams very quickly and is primarily responsible for the initial rise in the hydrograph during or immediately after a rainfall.

In densely vegetated, humid regions the infiltration capacity is high enough for soils to absorb all but the most intense rainfalls. Water percolating vertically through the soil may encounter a less permeable horizon and can be diverted laterally along the surface of this horizon to appear further downslope. Under intense storm conditions, such water can migrate through the largest soil pores, worm holes and structural openings at rates up to 0.2 m/hr on steep forest slopes and can contribute to floods. This water is termed subsurface stormflow (Whipkey 1965). Streams whose discharge is principally from subsurface stormflow respond an order of magnitude more slowly to a rainfall event and their

Table 1. Climate changes resulting from urbanization (Chagnon 1977).

Variable	Average Changes, as a Percentage of Rural Conditions Annual	 Cold Season	 Warm Season
Solar Radiation	-22	-34	-20
Temperature	+ 2	+ 4	+ 1
Humidity (relative)	- 6	- 2	- 8
Visibility (frequency)	-26	-34	-17
Fog (frequency)	+60	+100	+30
Wind Speed	-25	-20	-30
Cloudiness (frequency)	+ 8	+ 5	+10
Rainfall (amount)	+14	+13	+15
Snowfall (amount)	±10	±10	-
Thunderstorms (frequency)	+16	+ 5	+29

peak runoffs are an order of magnitude lower than streams receiving overland flow (Dunne 1978)

If the supply of water to the soil, from transport from upslope or from vertical transport, is sufficiently great, the soil may become water saturated. Some of the water traveling as subsurface stormflow emerges at the ground surface, is supplemented by direct precipitation on the saturated surface, and is termed satuarated overland flow. Saturated overland flow generally occurs well down hillslopes on fairly low gradients and travels at speeds of 0.3 m/hr to 100 m/hr. The contribution of saturated overland flow to the stream hydrograph is intermediate between overland flow and subsurface stormflow (Freeze 1972).

The combination of overland flow, subsurface stormflow, and saturated overland flow comprise direct runoff. Ground water occurs in saturated openings in the earth and provides the water to springs and to the fair weather flow of streams. The water table is the top of this saturated zone and natural discharge of ground water takes place where the water table is at or near the land surface. Part of this discharge is contributed to streams and constitutes baseflow, and part of the discharge is evaporated or transpired.

Evapotranspiration, that is, the direct discharge of water vapor to the atmosphere, depends on the availability of moist surfaces exposed to the atmosphere. The rate of evapotranspiration is a function of air temperature, humidity, wind, sunshine duration and intensity, and vegetational cover. On the scale of river basins, the actual rates of evapotranspiration are computed by the difference between precipitation and river discharge. Table 2 provides data on the Susquehanna and Delaware River basins. Figure 1 illustrates the basin locations.

It is instructive to compare the total freshwater discharge from the Susquehanna and Delaware River basins after significant modification of the watersheds with the basins before European man settled the area. Intuitively, most of us would agree that the seasonal discharge of fresh water would have been different when the watersheds were covered with mature forests. We would also probably agree that water quality parameters (particularly suspended sediment and temperature) could be significantly different. The factors that influence the infiltration of storm precipitation into the soil and the reduction of direct runoff on forest lands are soil structure and texture, degree of protection of the soil against raindrop impact, and the density of vegetative cover which intercepts part of the precipitation and, through transpiration, depletes soil moisture. The type, age, and density of forest cover is directly related to the amount of forest floor humus and surface litter, which, in turn impedes surface water flow, protects the soil surface, and retards or prevents freezing in cold weather. Ground fires, woodland grazing, logging or deforestation tend to destroy the humus layer and promote increased direct runoff.

A series of curves has been developed to show the relationship between given amounts of precipitation and predicted runoff for each of a variety of land uses (U.S. Soil Conservation Service 1972). For the Delaware and Susquehanna basins, cover types are woodland, grassland, cropland, idle land, and urban areas. The data for the Delaware basin are presented in Table 3 and the Susquehanna River basin in Table 4. Four

Table 2. River basin characteristics.

Delaware River Basin[b]

Region[a]	Av. Annual PPt (in)	Av. Annual Runoff (in)[d]	Area (mi^2)	Runoff[d] % of PPt
1	44	24	3881	54
2	45	21	958	47
3	45	25	947	55
4	44	21	969	48
Sub basin weighted average above Philadelphia	44	23		52
5[e]	43	16	2183	37
6[e]	43	15	2719	34
Basin Average	44	22	11657	50

Susquehanna River Basin[c]

Region[a]	Av. Annual PPt (in)	Av. Annual Runoff (in)[d]	Area (mi^2)	Runoff[d] % of PPt
1	38	21	4944	55
2	34	13	2604	38
3	37	18	3755	49
4	41	21	2975	51
5	38	20	4017	53
6	39	17	3406	44
7	41	18	2399	44
8	40	18	3410	45
Basin Average	39	18	27510	46

a) Regions indicated on Figure 1
b) Data from Delaware River Basin Report, Appendix K, 1960
c) Data from Susquehanna River Basin Report, Vol. 1, 1970
d) Runoff includes base flow and direct runoff
e) This area drains into the tidal portion of the Delaware basin

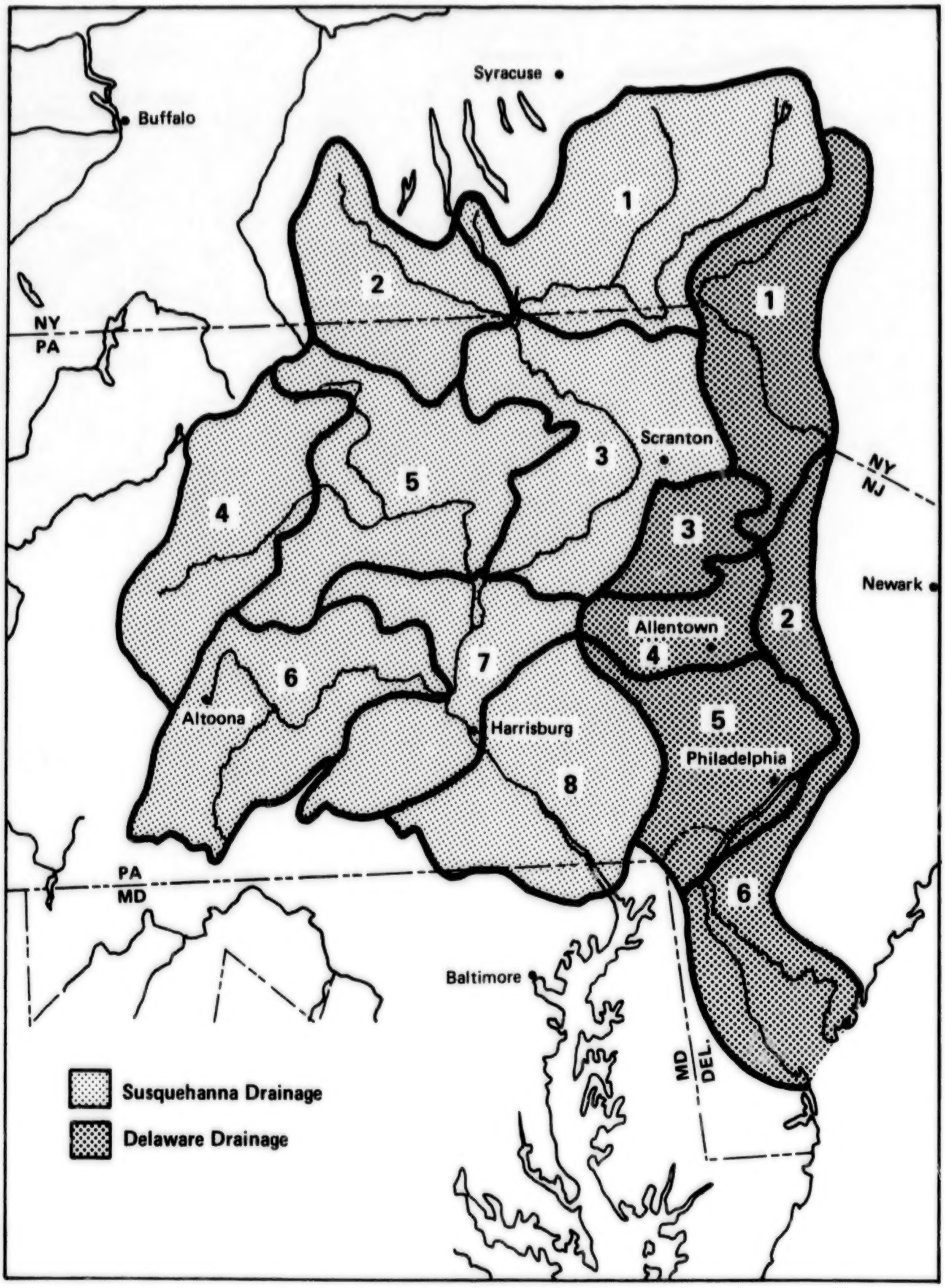

FIGURE 1 — Susquehanna and Delaware watersheds and sub-basins.

Table 3. Delaware River Basin, 1954 land use[a].

(1) Physiographic Area (Fig. 1)	(2) Soil Group[b]	(3) Cropland Acres (000)	Cropland Runoff CN	(4) Pasture Acres (000)	Pasture Runoff CN	(5) Woodland Acres (000)	Woodland Runoff CN	(6) Idle Acres (000)	Idle Runoff CN	(7) Urban Acres (000)	Urban Runoff CN	(8) Weighted Runoff by Area(1954) CN	(9) Total Area (All uses) Acres(000)	(10) Woodland Runoff	(11) Weighted Runoff (1600)[c] CN
	A	26	65	11	49	43	41	5	68	10	84		95	33	
1	B	162	73	76	69	1120	64	37	79	24	90	70	1419	53	59
	C	103	82	44	76	703	74	21	86	99	85		970	63	
Total Area		291		131		1866		63		133			2484		
	A	5	57	<1	49	2	42	1	68	--			8	34	
2	B	169	69	29	69	218	65	46	78	26	84		488	57	
	C	40	77	10	79	46	75	17	86	<1	91	70	113	67	59
	D	2	83	<1	84	1		<1	89	<1	92		4	78	
Total Area		216		40		267		65		28			613		
	A	9	61	<1	49	5	44	1	68	--			15	39	
3	B	101	69	6	69	101	66	12	79	--		74	220	60	66
	C	91	79	10	79	230	76	12	86	28	84		371	70	
Total Area		201		16		336		25		28			606		
	A	--		--		--		--		--			--		
4	B	154	71	25	69	72	65	13	79	2	84	75	266	57	63
	C	143	79	28	79	134	75	9	86	40	84		354	67	
Total Area		297		53		206		22		42			620		
	A	--		--		--		--		--					
5	B	306	72	32	69	74	65	30	79	165	84		607	58	
	C	350	79	83	79	287	75	41	86	3	90	76	764	68	64
	D	8	84	2	84	5	81	3	89	8	98		26	68	
Total Area		664		117		366		74		176			1397		
	A	50	66	3	49	49	42	23	68	<1	74		125	36	
6	B	416	76	41	69	490	65	66	79	5	84	73	1019	59	61
	C	164	83	15	79	104	75	23	86	289	78		595	69	
	D	--		--		--		1	89	--			1	78	
Total Area		630		59		643		113		295			1740		
Weighted Runoff By Land Use (CN)			75.2		72.5		68.4		80.6		83.7				

a Modified from Use and Management of Land and Cover Resources, Appendix K, Delaware River Basin Report, U.S. Army Corps of Engineers, 1960.
b See text for explanation.
c Assumes mature forest with 10% open or immature areas from forest fires.

Table 4. Susquehanna Basin land use data (1964)[a] (in thousands of acres).

Area	Cropland	Pasture	Woodland	Idle	Urban	Total	Runoff (CN)b
1	728	651	1381	304	92	3156	70
2	457	271	715	158	47	1648	70
3	511	193	1290	176	171	2341	72
4	142	31	1584	76	45	1878	74
5	393	81	1901	123	71	2569	74
6	437	123	1443	82	82	2167	75
7	404	66	715	102	83	1370	75
8	1086	242	644	160	146	2278	74
Total	4158	1658	9673	1181	737	17407	

a from Susquehanna River Basin Study, Appendix J, 1970

b based on CN data from Delaware Basin

soil groups have been classified on the basis of their ability to accept water at the end of long duration storms (U.S. Army Corps of Engineers 1960). Group A soils are highly permeable while Group D soils are relatively impermeable. The Soil Conservation Service has computed the soil versus cover complex number (CN) from field investigations of the Delaware basin watersheds and has developed a composite number for each physiographic area based on land use and area. This composite index represents the present (1954 for Delaware basin, 1970 for Susquehanna basin) hydrologic condition by physiographic area. Column 10 represents the CN for the given soil types assuming mature forest cover with 10 percent openings or immature forest due to natural fires. Column 11 is an estimate of the weighted CN for the year 1600, before significant impact by settlement. In order to relate the changes in the CN to changes in direct runoff, the relation developed in Figure 2 must be used. The curve represents runoff changes as a percentage of direct runoff for a unit change of CN. For example, if a precipitation event produced 1.5 inches of runoff for a CN of 70 and land use practices were instituted which reduced the CN to 69, there would be a 5 percent reduction in runoff. Similarly, if land use practices reduced the CN from 70 to 62 (8 points) there could be a 40 percent reduction (8 points x 5%/point) indirect runoff for a 1.5 inch precipitation event. Thus, land use treatments have a greater effect on storms of long duration and low intensity and a lesser effect on storms of high intensity. The curve in Figure 2 must be used with great care as the change in runoff decreases with increasing watershed size because part of the infiltration, the greater the base flow and the greater the evapotranspiration. Based on small watershed studies, approximately half of the additional infiltration will be reflected in increased baseflow and half will be lost to evapotranspiration.

A first approximation of the change in peak and low flows for the Delaware and Susquehanna basin is presented in Table 5. The present seasonal hydrograph for each basin would have been significantly altered under "All forest" conditions, with low flow about 10 to 15 percent higher, and high flows about 25 percent to 30 percent lower than at present. Average annual discharge (assuming similar precipitation) may have been significantly lower than at present (Muller 1966).

While such seasonal alterations in major system hydrographs may seem high, direct evidence of the increase in low flow conditions on the Delaware River has been reported (USACE 1960). The Delaware at Port Jervis, N.Y. has experienced a 25 percent increase in low flow (watershed area 3,076 mi^2) during the period July-October 1915 to 1954. This increase in base flow is attributed to a "general increase in cover conditions and management which is known to have occurred".

A much more sophisticated estimate could be made by computing a climatic water budget for sub-basins in each of the watersheds to estimate streamflow (Mather 1979). In addition, suspended sediment and water quality parameters could be modeled (Simmons and Heath 1979) to provide an estimate of pristine conditions.

GEOLOGIC EVIDENCE PALEOSALINITY

The model for long term salinity change in an estuary experiencing

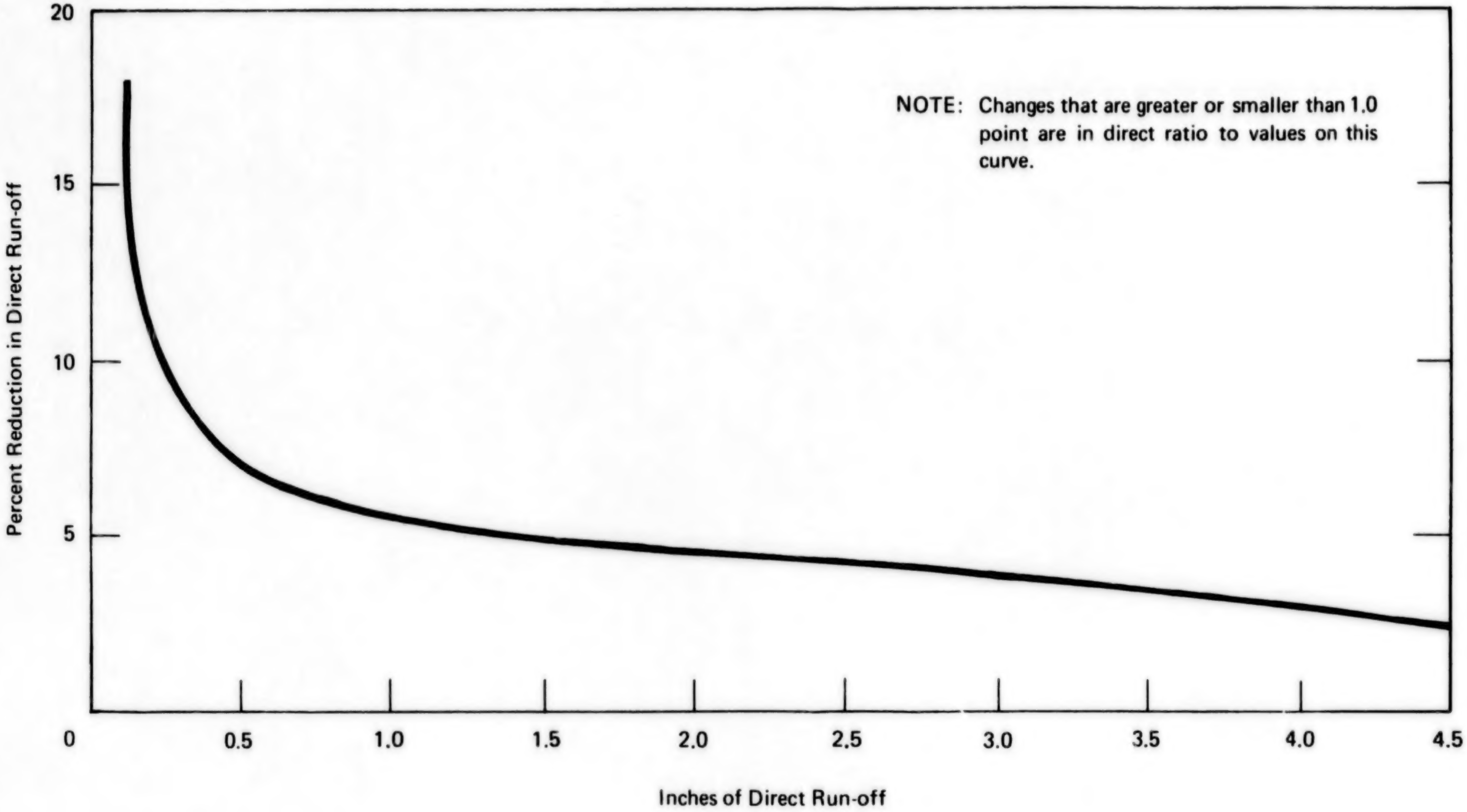

Figure 2. Runoff changes for 1.0 point change in index numbers (from Delaware River Basin Report, Appendix K, Use and Management of Land and Cover 1960).

Table 5. Change in low and peak flow patterns for Delaware and Susquehanna Basins (1954 and 1964 respectively) assuming all forested watersheds.

Delaware River Basin
(above Philadelphia

Physiographic Area (see Fig.1)	Present Index Number (CN)	(CN)[b]	Pre Development Low Flow[a] % Increase	Peak Flow[a] % Increase
1	70	59	11	34
2	70	59	11	34
3	74	66	8	28
4	75	63	12	36
weighted average for basin	71		11	32

Susquehanna Basin

Physiographic Area (see Fig.1)	Present Index Number (CN)	(CN)[b]	Pre Development Low Flow[a] % Increase	Peak Flow[a] % Increase
1	70	59	11	34
2	70	60	10	31
3	72	60	12	42
4	74	64	10	31
5	74	66	8	28
6	75	66	9	29
7	75	65	10	31
8	74	66	9	29
weighted average for basin	73	62	10	3

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[a] computed directly from USACE, Delaware River Basin Report, Appendix K, 1960

[b] CN's from Table 3 and Table 4

rising sea level predicts that, at a specified location salinity will increase as a function of sea level rise provided that sedimentation rate is less than sea level rise. Along the mid-Atlantic coast of the United States, sea level has risen monotonously for the last 10,000 years, though there is evidence that short, perhaps cyclic, falls in sea level with amplitudes of about 1 m have occurred, particularly in the last 4,000 years. There is no evidence to indicate that during the latest sea level rise, northern Chesapeake Bay has been higher than present. Thus, one would predict that, at a location in northern Chesapeake Bay (the estuary of the Susquehanna River), salinity has increased over time up to the present.

The discovery of shell middens, consisting of the eastern oyster, Crassostrea virginica, in an area of northern Chesapeake Bay at Worton Point (Kraft and Wilke personal communication) upstream from the oysters' present, salinity-controlled habitat, has cast doubt on the general applicability of the rising sea level-increasing salinity model.

A long core was taken in the vicinity of Hart Island, northern Chesapeake Bay. The site is a buried oyster bar which is being dredged for recovery of oyster shell. Shell material was examined for the pres ence of attached organisms which could provide evidence of past salinity. The presence of boring sponges was evident on some shells.

The boring sponges, or Clionidae, are a serious pest to the cultivation of oysters in almost all estuarine environments. Cliona bores into calcareous objects as a means of securing stability. The bulk of the sponge grows outside of its shell substrate and appears as a dome-shaped or vase-shaped growth.

The most important work on the boring sponges has been that of Old (1941) in which the species of Cliona occurring on the Atlantic coast of North America are thoroughly described and illustrated. Hopkins (1956), working in Louisiana estuaries, undertook the first really important study of the distribution of the distribution of Cliona species in relation to salinity. He found a positive correlation between the occurrence of Cliona celata and higher salinity and the occurrence of C. truitti and C. vastifica and lower salinity, the relationship which he found was based on the number of days per year that the sponges were subjected to a salinity level below their critical tolerance, and he found that C. truitti and C. vastifica were able to withstand lowered salinity much better than C. celata. The absence of C. celata can, according to Hopkins, be taken to indicate a salinity below 10 percent one-fourth of the time and below 15 percent one-half of the time. The absence of C. truitti is indicative of a salinity below 10 percent at least half of the time. The species distribution of Cliona can therefore be used as a measure of salinity level.

Oyster shells from the Hart Island core were examined for the presence of Cliona tunnels; and when such tunnels were present, an attempt was made to identify the species which had made them.

There are four species of Cliona occurring naturally in the Chesapeake Bay: C. celata, C. lobata, C. truitti, and C. vastifica. C. celata can easily be differentiated from the other three species occurring in the bay by the size of the holes it leaves in the shell substrate. Holes made by C. celata are 1.5 to 2.5 mm in diameter, while those made by C. lobata, C. truitti, or C. vastifica are 0.2 to 0.5 mm in diameter (Hopkins 1956). The separation of the latter three species requires solution of the oyster shells and microscopic examination of spicules.

Shells from three locations around the bay were examined macroscopically, and the presence or absence of sponge holes noted. When holes were present, C. celata was separated from C. lobata, C. truitti, and C. vastifica; but no attempt was made to differentiate between the latter three species. The data, then, are a measure of the relative abundance of C. celata, and appear in Table 6.

The oldest shells from Hart Island had very few tunnels from boring sponges or any other organism. They were large, and had very hard shells. Most had no holes in them at all. In all probability the salinity level, at the time these deposits were laid down, was relatively low--possibly somewhere around 10 percent. The shells above them were extensively eroded and tunneled, and tended to be somewhat smaller. Many of the holes in these shells were made by Cliona celata, suggesting a salinity level closer to 15 ppt. In all probability, then, the area around Hart Island was undergoing a substantial increase in salinity during the time interval represented from -3m to -1m. This conclusion is especially interesting in view of the fact that the present salinity level in this area is below the critical level for Cliona of any kind, and Cliona does not currently occur there. The direction of the change in salinity at Hart Island, then, has not always been the same.

Lack of multiple radiocarbon control points precludes an analysis of when this apparent higher salinity occurred in the northern Chesapeake and an interpretation of its cause. If the maximum salinity occurred several thousand years ago, then a climatic shift, perhaps associated with the Altithermal or Iron Age may be invoked. If the maximum occurred near 500 years BP, then perhaps land use practices in the watersheds since that time may be involved.

SUMMARY AND CONCLUSIONS

A first approximation of the freshwater discharge, assuming modern precipitation, from the Delaware and Susquehanna, indicates that wholly forested basins deliver different seasonal distributions for both watersheds than does the present land use mix. Low flows would be higher and peak flows would be lower. We cannot determine whether total annual discharge was different from today either because of higher evapotranspiration or lower annual rainfall, or both.

Salinity in the upper Chesapeake was higher than at present as indicated by the presence of oysters and associated organisms in areas where present seasonal salinity is too low for their survival.

SPECULATION

Table 7 illustrates the global needs for major foodstuffs. A subtle shift in world food production could alter significantly the agricultural needs for irrigation water. A 10 percent to 20 percent drought related reduction in North American grain productivity would not lead to food deficits in North America but will have drastic implications for the

Table 6. Hart Island, Chesapeake Bay, oyster bioherm core (water depth 3.5m).

Depth below bottom (m)	Sediment character	*C*. *Celata* borings	Other sponge borings	Both	Neither
0-1	sandy silt	0	0	0	100
1-2*	with	5	25	15	55
2-3	abundant	20	10	70	0
3-4	oyster	16	20	10	54
4-5	shell	0	25	0	75
5-6		0	20	0	80

**Crassostrea* shells from this zone were radiocarbon dated at 545 ± 90 years BP.

Table 7. Grain exports and imports (from Brown 1975) (10^6 metric tons).

Region	1934-38	1948-52	1960	1970	1976
North America	+ 5	+23	+39	+56	+94
Latin America	+ 9	+ 1	0	+ 4	- 3
Western Europe	-24	-22	-25	-30	-17
Eastern Europe and USSR	+ 5	0	0	+ 1	-25
Africa	+ 1	0	- 2	- 5	-10
Asia	+ 2	- 6	-17	-34	-47
Australia and New Zealand	+ 3	+ 3	+ 6	+12	+ 8

countries dependent on North American imports. The development of land based bioenergy, highly touted as a partial solution to the U.S. energy shortage, may increase the need for fresh water in hinterland basins. Further, meterological and hydrological evidence suggests that 10 percent to 15 percent changes in precipitation are common and that what we think of as normal climate, at present, is not normal in the longer perspective of recent centuries (Bryson 1975). Finally, in addition to whatever nature has in store for us, we now recognize that man has the capability to modify climate on a local, regional, and global scale.

Even in the short term (say the next two decades), it may not be possible to guarantee a certain absolute volume of fresh water to an estuary.

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DISCUSSION

Question: J. L. Hasseled, Citrus County Florida. I have two questions that are rather related, sir. In your studies have you evaluated the percentage of improvements as to runoff in large residential type developments by the design of retention areas and swales? And the second part of that question is, will a tenurial land use or zoning regulation to accomplish this effect be detrimental to the estuary in the long run?

Answer: The answer to the first part of your question is no. I have not looked at the improvements or litigations that can be made in land practice and what their effects would be. The answer to the second part of your question, as to whether or not such effects would be deleterious, is that the Atlantic Coastal Plain Estuaries were much different naturally in pre-colonial times than they are at the present time. I think we all would agree to that. But I'm speaking about freshwater flows. What I'm saying is, we have gotten to where we are in freshwater discharge in coastal plain estuaries by not knowing what we were doing. As land use practices improved--and I'll say improved from a number of perspectives--Soil Conservation Service has technological capability at the present time to reduce the suspended sediments by a factor of five for most of these Atlantic coast watersheds. For instance, no-till farming is going to save farmers money for energy and they are going to no-till. No-till reduces direct sediment runoff by a factor of two or three in itself. If this happens to a significant extent in these Atlantic coast basins, we are going to see a decrease in the base flow, and an increase in the peak flow. Now, that deals with the freshwater aspect. With respect to the suspended sediment, we could really be in trouble if we did that. For instance, I cannot think of a biologist who has looked at the primary production of an Atlantic Coastal Plain Estuary, who has not said that the system is light limited, that limit on primary production is light. Given the present mix of nutrient inputs that we provide the estuaries, if we reduced suspended sediments by 50 percent, and increased the light available in those estuaries, we might have a biological disaster.

Question: In other words, your moving of the freshwater flow up and down could have a deleterious effect on the entire estuary?

Answer: Certainly it could.

PRECIPITATION TRENDS AND VARIABILITY IN THE VICINITY OF NORTHWEST GULF COAST: 1900-1980

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ABSTRACT

South Texas and adjacent northeastern Mexico comprise a vast, nearly uninterrupted subtropical semiarid-to-subhumid climatic environment. Interestingly, it is the only east-coast subtropical steppe on our planet. Like all semiarid areas, however, both the margins and internal moisture availability of this climate region are highly dynamic and unreliable. For example, within the past quarter-century, several stations within 50 miles of the Gulf of Mexico have received as few as eight and as many as 65 inches of precipitation in a given calendar year. As a result, estuaries along the northwest Gulf of Mexico experience wide year-to-year variations in freshwater inflow and, in turn, tend to alternate between hyper- and hypo-saline conditions. This paper describes, depicts graphically, and statistically analyzes the regional climatology of semi-arid South Texas and northeastern Mexico, with particular emphasis on twentieth-century precipitation fluctuations, trends, droughts, and "spells".

INTRODUCTION

A vast, nearly uninterrupted semi-arid, subtropical region lies between 23° and 32° North Latitude in North America, bounded to the east by the Gulf of Mexico and to the west by the Sierra Madre Oriental mountain range. This steppe area, identified by Trewartha (1968) as one of the earth's unique "problem climates", includes all of southern Texas in the United States and much of the states of Nuevo Leon and Tamaulipas in Mexico. Physiographically, the region is flat to gently-rolling coastal plain, presently covered by scrub brush intermixed with such xerophytes as cacti and yucca.

Climatically, it is almost a classical example of a subtropical steppe, becoming first subhumid and then humid to the east and south, grading into desert to the west, and into middle-latitude semi-arid to the north/northwest. Mean annual temperatures approximate 75° F. (23.9°C), the growing season generally exceeds 300 days, and average yearly rainfall ranges between 15 inches (380 mm) and 30 inches (720 mm) (Figure 1). The precipitation regime demonstrates a monsoonal tendency, with 65 percent of total annual rainfall coming during the high-sun period. Nonetheless, the distribution is bimodal, with minima occurring both in spring (usually March, when both mid-latitude cyclonic and tropical convective precipitation are at a nadir) and in midsummer (typically July). Perhaps one-

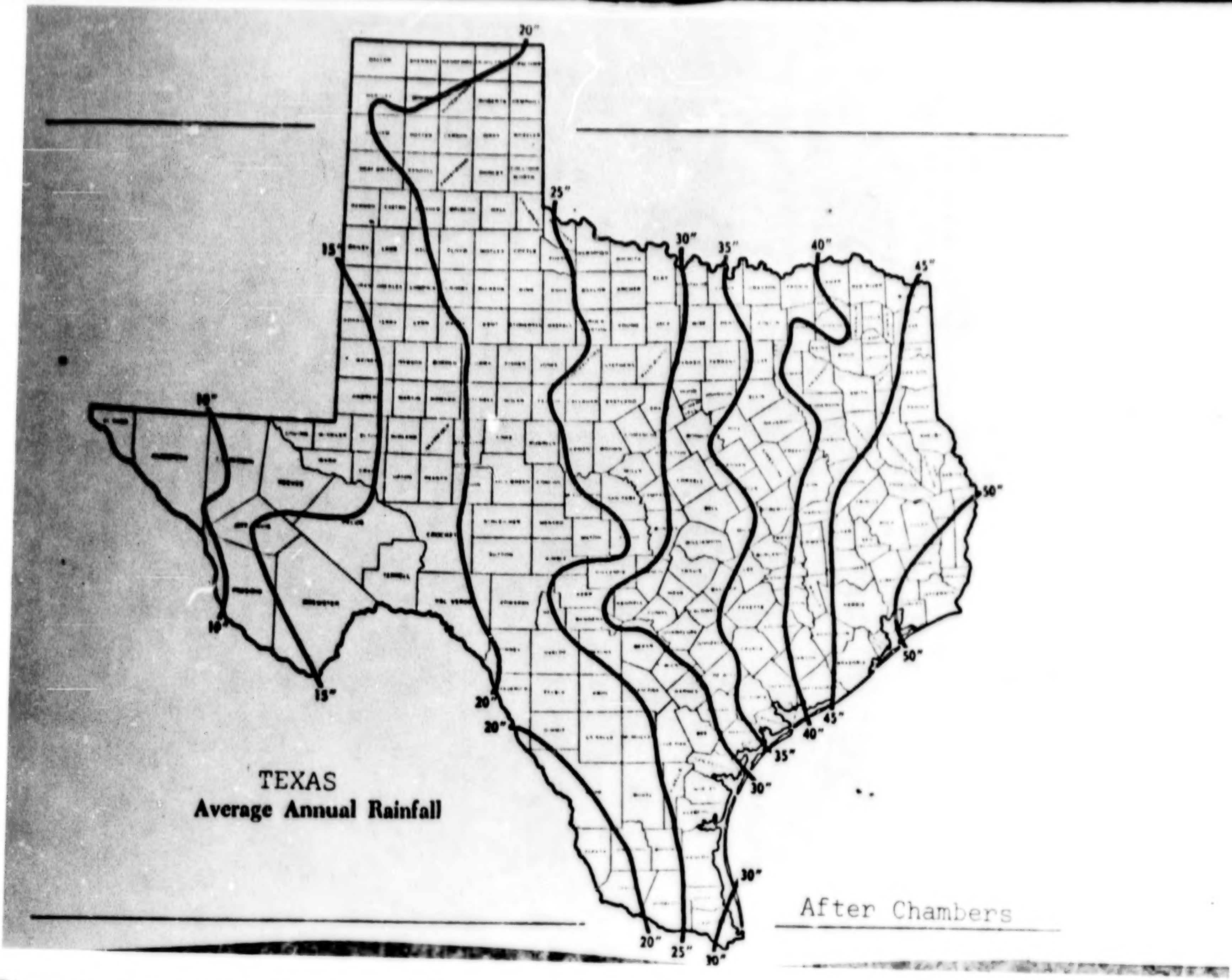


Figure 1. Texas annual average rainfall.

half of the precipitation of late summer/early fall (especially September) is associated with tropical disturbances.

Summers are long, hot, oppressively humid, and intensely "bright" (an ozone "window" has been reported in the stratosphere over the eastern portion of the region). Mean summer maximum temperatures are near 95° F (29.4° C), while minima remain between 75° F (29.4° C) and 80° F (26.7° C). Winters are pleasantly mild: mean January temperature is about 60° F (15.6° C), with only occasional frost. Snow is rare in Texas, being reported about once each decade, and virtually nonexistent in northeastern Mexico.

In both Texas and Mexico, the greater part of the area is utilized for cattle grazing, but highly productive intensive commercial agriculture is practiced where water supplies permit: milo and cotton in the subhumid northeastern section of South Texas; winter vegetables, citrus fruits, and sugar cane on irrigated lands along the Rio Grande River between the two countries; and sisal (hemp), banana and citrus fruit plantations toward the Tropic of Cancer in Mexico. (Some peasant or subsistence agriculture is also practiced on non-irrigated farms in northeastern Mexico.) It is, therefore, a region of surprising agricultural diversity and importance, one which is a significant supplier of grain sorghum, cotton, citrus fruits and cattle to the international market, and yet it is a steppe which has largely been ignored by research climatologists in both the United States and Mexico.

One reason for this neglect may lie in the fact that the genesis of of this climatic zone has never been well-understood. Trewartha put it thusly: "Along the west gulf coast both in northeastern Mexico and in adjacent parts of Texas, there is a semiarid region which appears out of place. Other parts of the gulf coast in both Mexico and the United States are wet. No adequate explanation for this dry region exists" (Trewartha 1968). Interestingly, the region may not only be unique in North America but in the world: according to most of the accepted climatic classifications, this appears to be the only east-coast subtropical (20° to 30° latitude) steppe on planet earth. (Somalia and Patagonia are, respectively, more appropriately described as equatorial and middle-latitude in nature.)

"The incongruous feature is that this part of the west-gulf littoral should be so deficient in precipitation considering the fact that in summer it lies within a flow of surface easterlies with an extensive body of warm water to windward. Advected moisture seemingly should be abundant...But limited Gulf of Mexico tropical waves and related storms decline in numbers and intensity toward the northwestern portion of the gulf" (Trewartha 1968) (Figure 2).

"Whatever its cause, the result is a curious semi-arid zone in which humidity and sensible temperatures are, more often than not, unpleasantly high or oppressive but rainfall is infrequent. For this reason, farmers in South Texas refer to it as their 'desert jungle'."

TWENTIETH-CENTURY CLIMATIC FLUCTUATIONS

DATA AND METHODS

The primary goal of this research program was to answer two

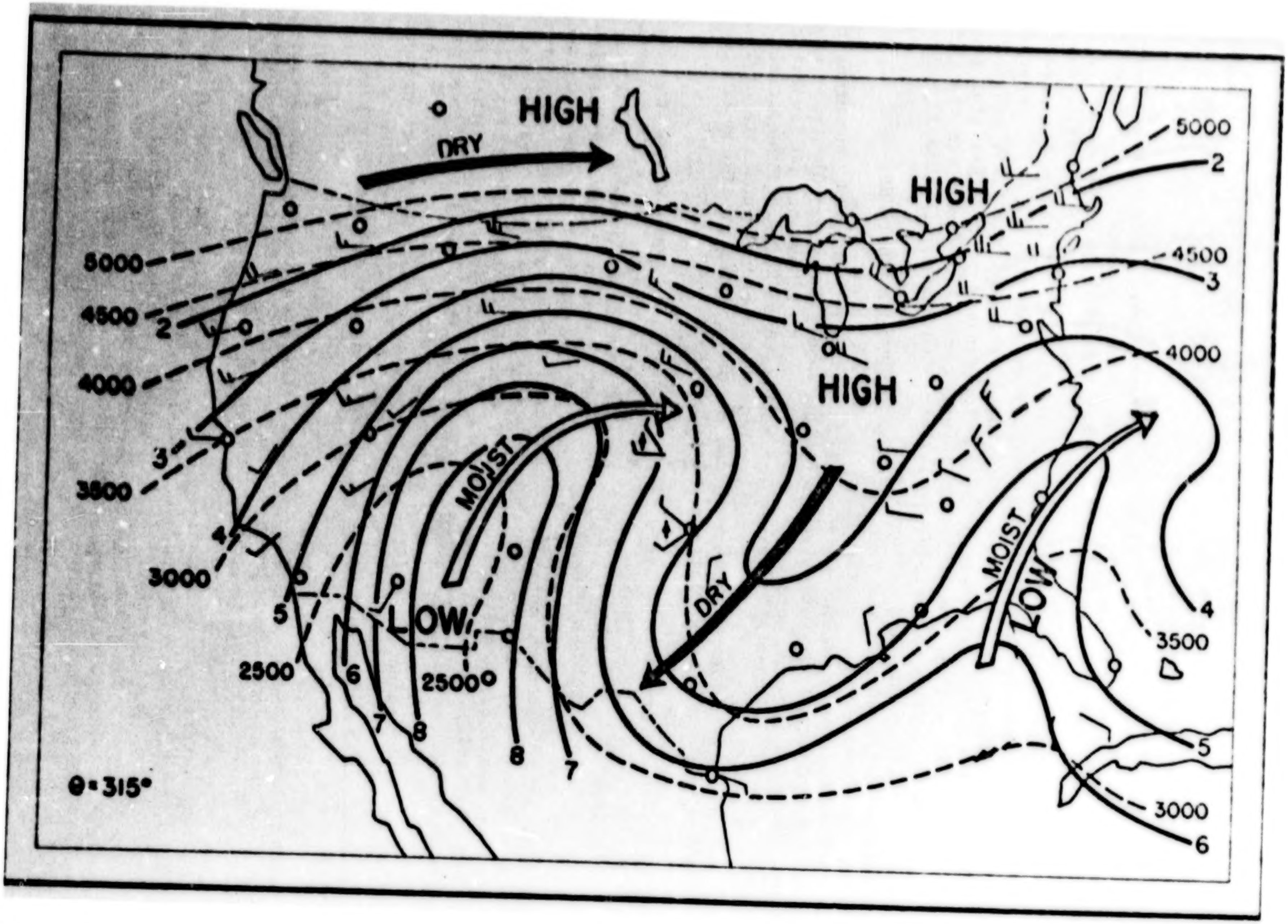


Figure 2. Average summer isentropic chart.

questions: (1) Has this semiarid region experienced any detectable cycles or climatic periodicities during the 20th century? and (2) have significant (longlasting) trends or "spells" of climate occurred and, if so, of what nature and when?

To study these problems, raw climatic data for approximately 50 meteorological stations in semi-arid Texas and 40 stations in northeastern Mexico were obtained from the U.S. National Climatic Center (Asheville, N.C.) and the Mexican National Hydrometeorological Office (Mexico D.F.). Of these, 10 widely-spaced stations within each of four sub-regions were isolated and subjected to intensive scrutiny. These subregions were: (1) Northeastern Mexico (coastal plain only); (2) South Texas; (3) Central Texas; and (4) the High Plains or North Texas (Figure 3). (The latter two were outside the scope of this report and, hence, are not included herein.)

In the United States, most of the stations had periods of record dating from 1900, although most had some interruptions. In Mexico, several stations had records dating from 1921, but the majority were established between 1925 and 1935.

In each sub-region, data for all 10 stations were combined and averaged to provide a number of useful statistics. First, mean annual regional temperature, mean maximum and minimum temperatures, and five-year running or "moving" averages to temperature were calculated. However, it quickly became apparent that the temperature variables manifested no discernible cycles, trends, or even showed much variability (i.e., the curves were almost perfectly flat). Thereafter, attention was focused upon precipitation, which is both far more variable and crucial to agriculturalists in Texas and Mexico.

Graphs were then prepared depicting the combined year-by-year average regional precipitation (all 10 stations combined) in each subregion, as well as four other parameters: median rainfall, five-year moving averages of rainfall, and maximum and minimum year values (for the 75-year period in Texas and that of 1921-1975 to Mexico) (Figure 4).

REGIONAL CYCLES AND TRENDS

In their monograph on drought in the Sahel, Katz and Glantz -- using the work of Bunting and Yevjevich -- report that "No established trends or periodicities (of annual rainfall) can be detected or confirmed (in the Sahel)" (Katz and Glantz 1976).

Conversely, such authorities as Mitchell, Thompson, and W. O. Roberts have reported a "drought cycle" of 20 to 22 years in the middle-latitude Great Plains steppe of Western United States. This cycle correlates impressively (albeit only statistically) with a corresponding cycle of solar sunspot activity. In that region, climatic conditions seem to have alternated between wetter and cooler than average in "even" decades (e.g., the 1920's and 1940's) and drier and warmer than average in "odd" decades (e.g., the 1930's, 1950's, and 1970's), a cycle which tree-ring data suggest has persisted for several hundred years (Norwine 1978).

Although spectral analyses of rainfall statistics are as yet incomplete, preliminary results strongly suggest that South Texas and Northeastern Mexico are more like the Sahelian model than that of the

STUDY SUB-REGIONS

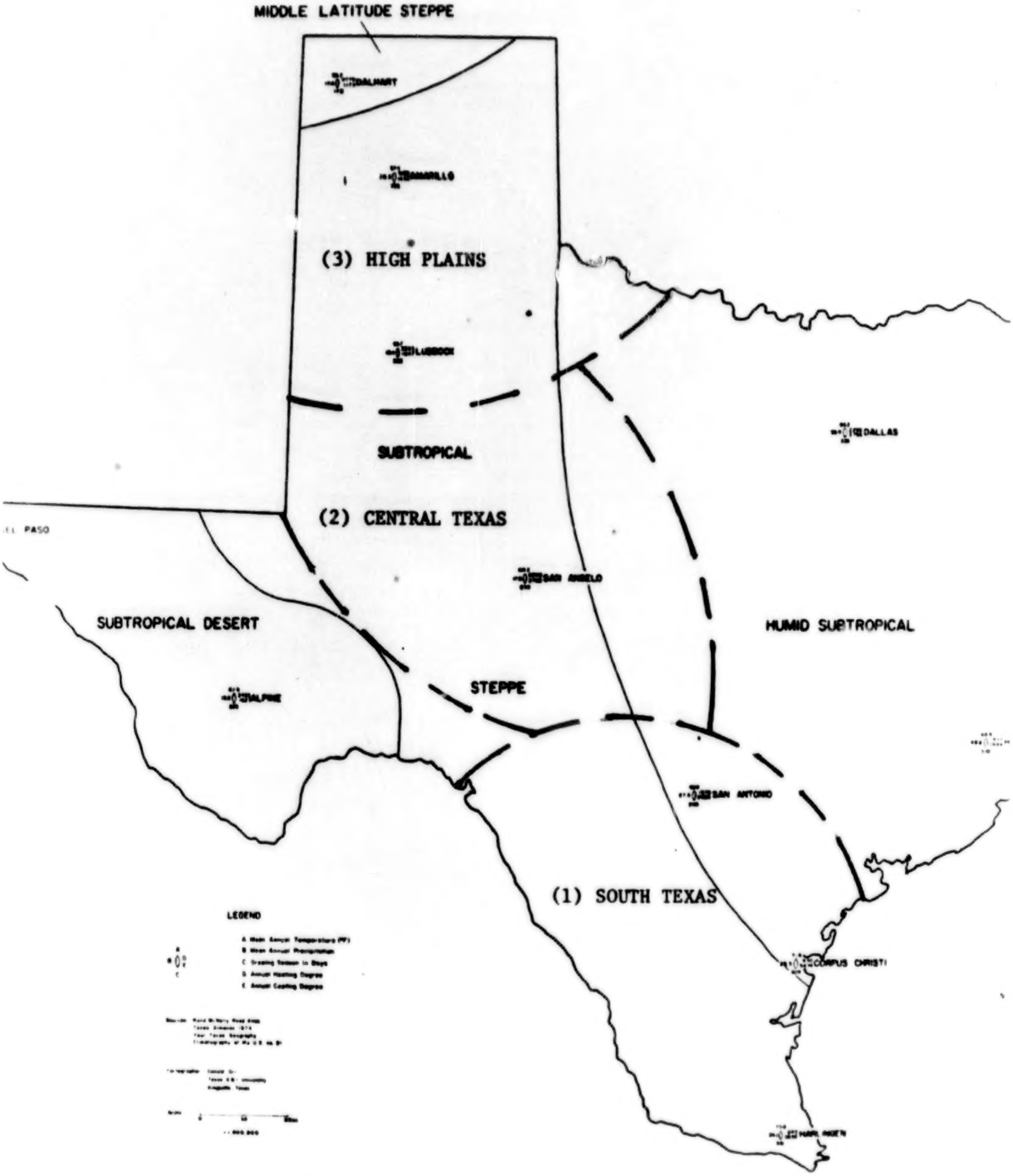
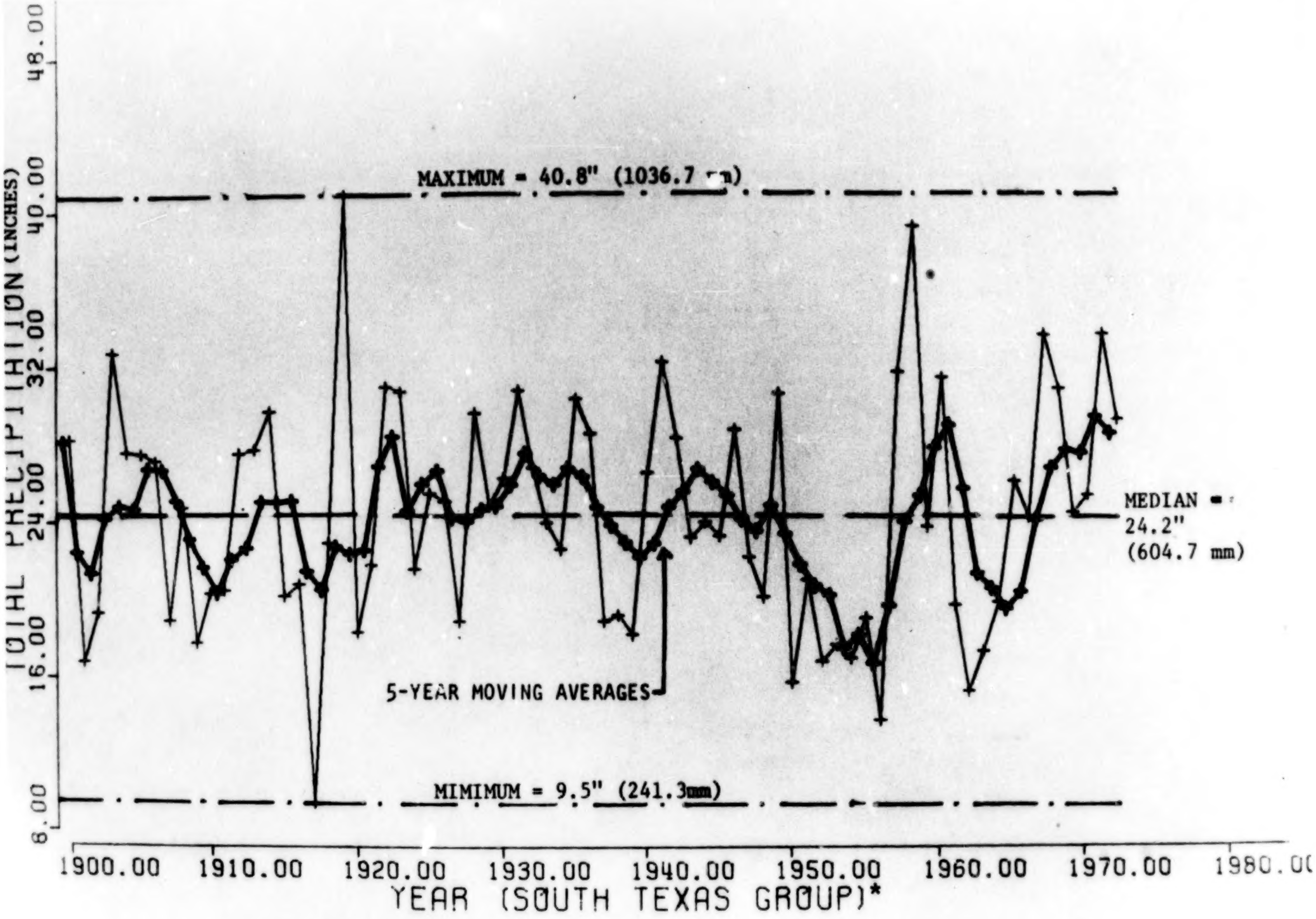


Figure 3. Climatic regions of Texas.



*Meteorological Stations

- Beeville
- Brownsville
- Corpus Christi
- Cotulla
- Eagle Pass
- Kingsville
- Laredo
- Rio Grande City
- Sarita
- San Antonio WB AP

Figure 4. Combined year-by-year average regional precipitation 1900 to 1970.

Great Plains. That is, while several illdefined "trends" do seem to appear in the record, no cycle with any predictive value is discernible.

RESULTS AND DISCUSSION

We shall examine the precipitation plots for both subregions, beginning with the subtropical steppe of South Texas.

South Texas. - In South Texas, we find the typical subtropical semiarid type atypically located: median rainfall for the period is near 25 inches (600 mm), with extreme variability in terms of departure from that value being the rule rather than the exception. Extremes ranged from a regional annual minimum of 9.5 inches (240 mm) in 1917, when the area was briefly true desert, to a maximum of 41 inches (1,040 mm) in 1921. This predominance of exaggerated unreliability is further borne out by the failure of the Great Plains type 20-year rainfall cycle to appear in the record. Major causes for this difference must include the lower latitude of this region and the varying influence of dynamic tropical storm paths upon it.

Two prolonged "trends" may be noted: (1) a 25 year moist period from 1922 to the late 1940's, with a minor interruption in the late 1930's; and (2) a distinct 10-year drought during the 1950's. Precipitation regimes prior to 1925 and after 1960 are perhaps best considered as typically erratic.

Northeast Mexico - Northeastern Mexico is drier than South Texas, but precipitation patterns appear to be less variable and observable trends are longer in duration and more distinct than in southern Texas. Median regional precipitation does exceed 20 inches (530 mm), with an annual maximum of 40 inches (1025 mm) and a mimimum of 14 inches (340 mm). The period of record for these 10 stations is less complete than in the United States, dating from 1921 (with missing data at nearly every station). Therefore, interpretation of the plot of five-year running averages for this region is risky and even rather premature (Figure 4 and 5).

Having stated that caveat, three and possibly four interesting trends in the graph may be noted (Figure 5). First, the period of 1927-1945 (18 years) was consistently moist in northeastern Mexico. Observe that this phase corresponds to its counterpart in South Texas but is both wetter and longer in duration. Secondly, a 20-year dry period began around 1945 which did not completely terminate until 1965. Again, this trend has a corollary "dry spell" in southern Texas, but in Mexico it is much more consistently dry, lacking the interruptions of wet years experienced north of the border. Finally, the period of 1965-1975, as in South Texas, was distinctly moist (a trend which personal observation indicates persisted at least through 1976). If one wished to be particularly bold in interpreting the plot, it could be postulated that the 1920's represented the end of a dry period similar to that of the 1950's. Unfortunately, records prior to 1921 which might confirm or contradict this hypothesis are not available.

RECENT PRECIPITATION TRENDS:

BAFFIN BAY, TEXAS

Baffin Bay is a large, shallow estuary located approximately 30 miles south of Corpus Christi on the Texas coast. Here, the rate of

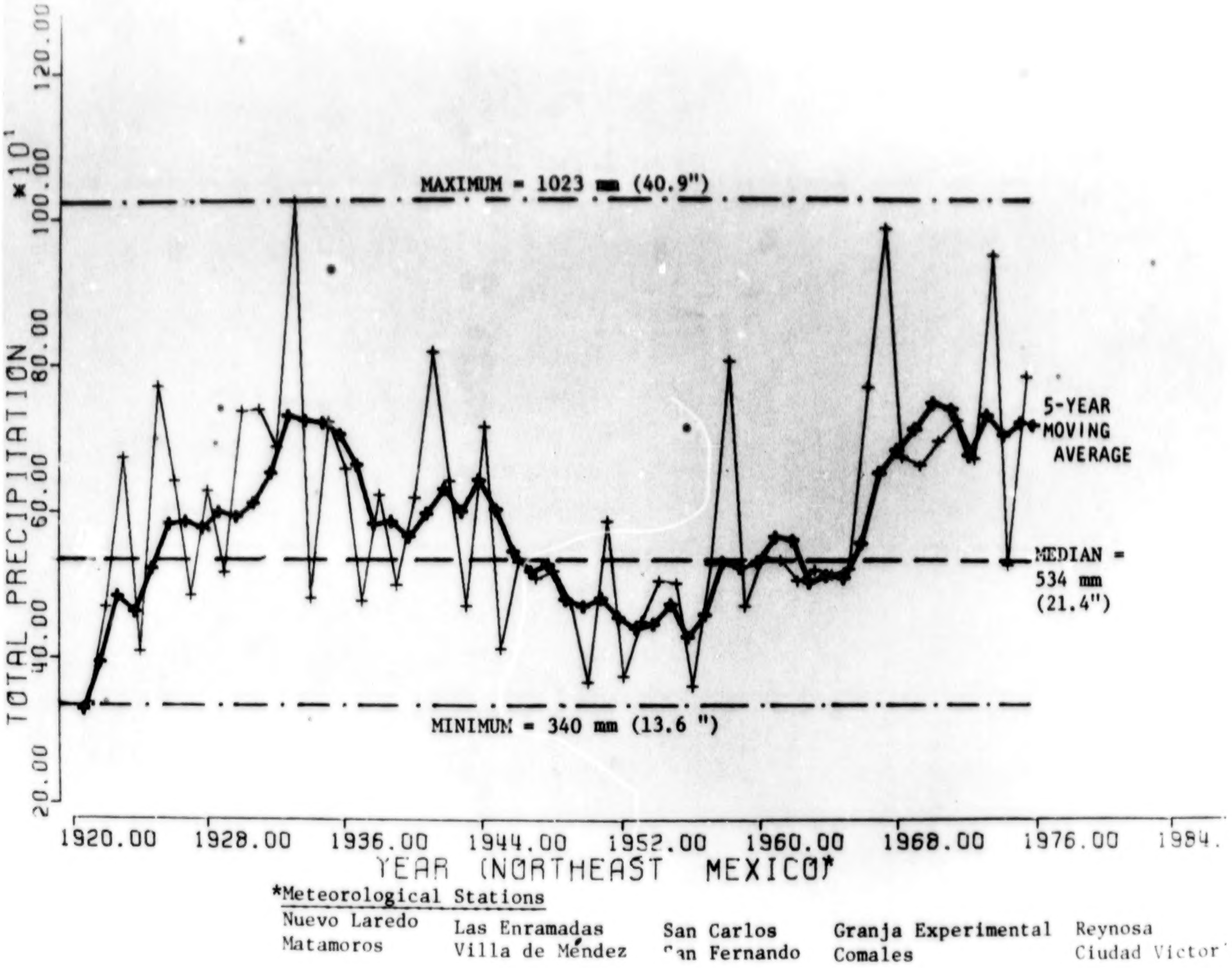


Figure 5. Combined year-by-year average regional precipitation 1920 to 1976.

evaporation consistently exceeds precipitation and results in an average annual moisture deficit of from 19 to 28 inches. Evaporation has its greatest affect during the summer months when air temperatures are at their annual maximum, rainfall is low and hot tropical winds blow consistently from the south and southeast. Average annual rainfall in adjacent Kennedy and Kleberg countries from 1931 to 1960 was 26.55 inches.

Of greater importance than the low annual rainfall budget in determining bay salinity is its variability and the nonuniformity of its distribution (e.g. generally rendering the bay either hyper or hyposaline). Rainfall is normally concentrated during two periods of the year, in early fall and, generally associated with tropical disturbances, to a lesser degree in late spring and early summer. Examination of the 62-year rainfall record for Kleberg country beginning in 1918, shows that monthly accumulations of more than 10 inches have occurred once each in January and April; twice each in May, June, and July, nine times in September, and three times in October. Although the majority of the annual rainfall is often equally distributed during late fall, winter, early spring, and mid-summer, the torrential rains of May-June and September-October result in runoff that significantly affects bay salinity.

A general classification of south Texas moisture conditions presented by Behrens and Watson (1973) states the following: less than 19 inches of rainfall drought; 19 to 24 inches - dry years; 24 to 32 inches - normal years; above 32 inches - wet years. Coupling this scheme with rainfall records from 14 to 20 collecting stations in the greater Baffin Bay and Upper Laguna Madre watersheds indicates that conditions during the last seven years were as follows: 1973-wet; 1974-dry; 1975-normal; 1976-wet; 1977-borderline dry/normal; 1978-normal; 1979-wet (See Figures 6 and 7) (Cornelius 1980).

CONCLUSIONS

It has been demonstrated that the steppe region adjacent to the western Gulf of Mexico has been characterized during the 20th century by pronounced variability and nonuniformity of precipitation. The normal salinity of such estuaries as Baffin Bay is therefore either hypersaline (when dry) or hyposaline (when moist). The result is an extraordinarily dynamic complex extuarine ecosystem, one which may well be unique among American estuaries.

ACKNOWLEDGMENTS

This report represents one phase of an ongoing longterm study of climatic variability in subtropical South Texas and northeastern Mexico. The invaluable assistance of Steve Cornelius, Ralph Bingham and Rosalia Vidal Zepeda is gratefully acknowledged. Support was received from Texas A & I University, the Cesar F. Kleberg Wildlife Conservation Foundation, the National Science Foundation, and the National Center for Atmospheric Research. Any remaining shortcomings in this work are, however, solely the fault of the author. (With one caveat: as an object lesson in the atmospheric caprices of South Texas, Hurricane Allen --second most powerful in American history -- struck as this manuscript was being prepared on August 8 to 11, 1980. Some portion of the uneven quality of the graphics and text, therefore, may

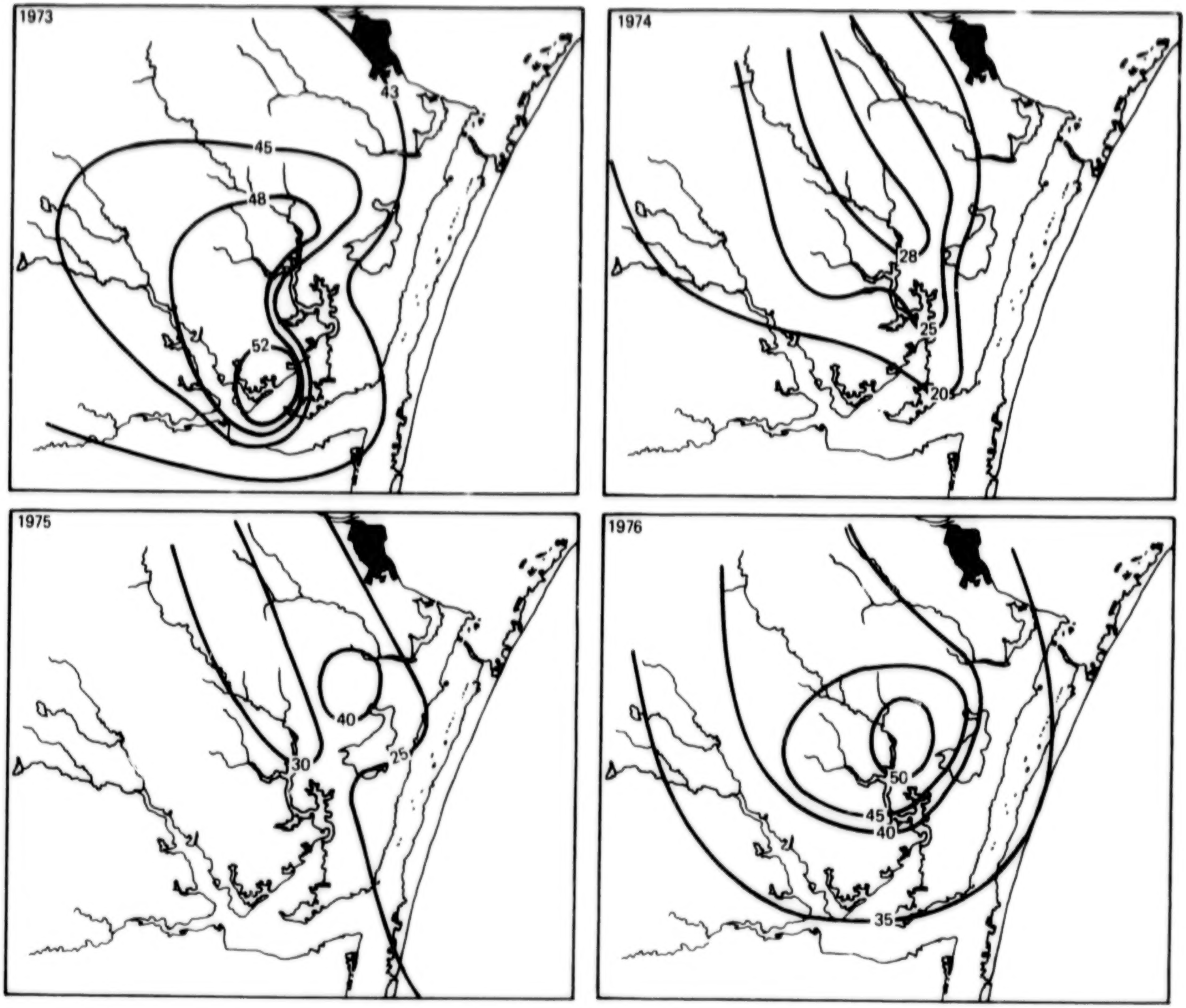


Figure 6. Wet, dry and normal years 1973 to 1976.

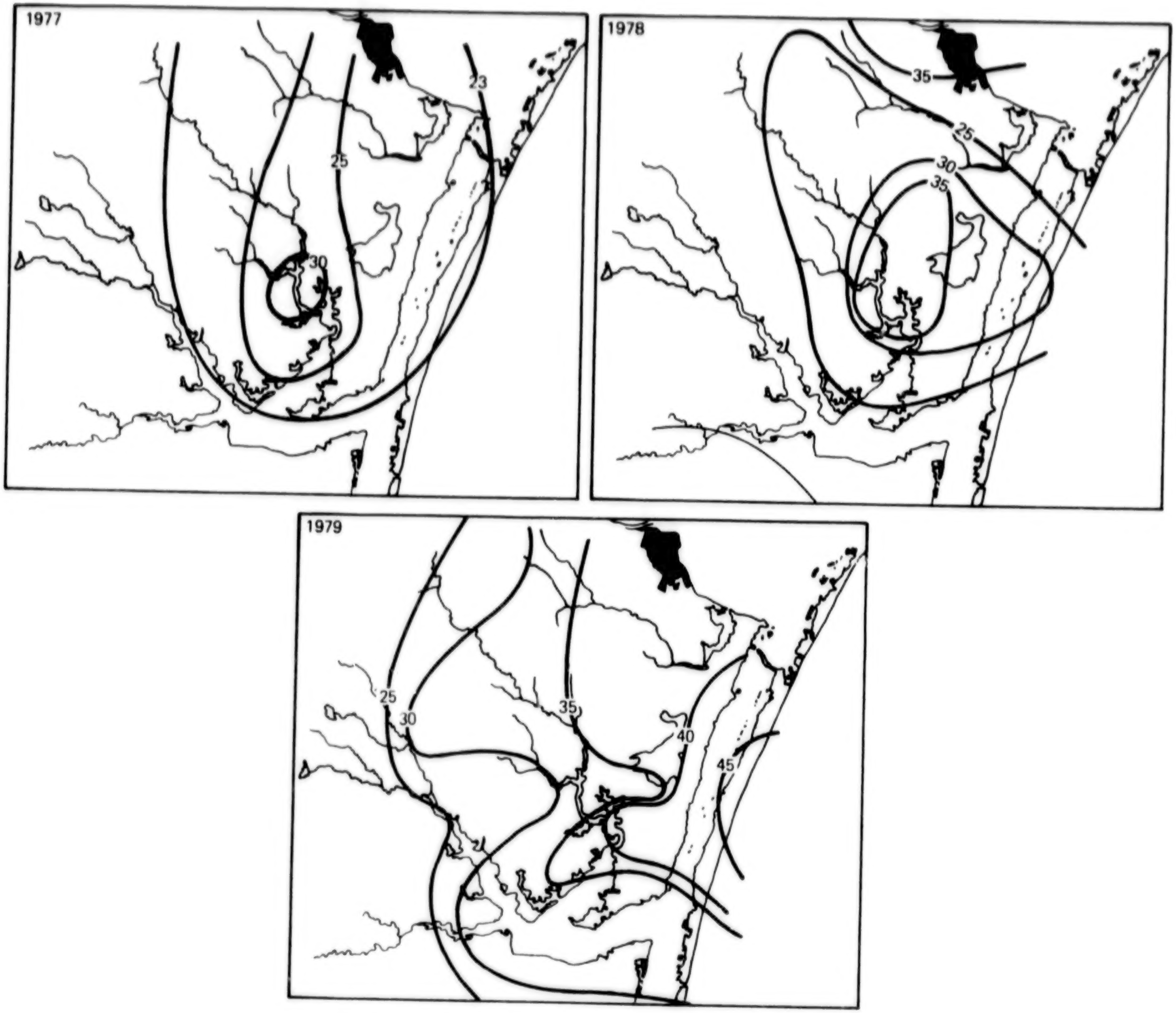


Figure 7. Wet, dry and normal years 1977 to 1979.

fairly be attributed to the author's Lincolnesque use of candlelight...) Twenty plus inches of rain from Allen ended a year-long drought (only 9 inches had been received in 1980 until August 8).

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RAINFALL-RELATED TRENDS IN THE STRUCTURE OF A FISH-CRUSTACEAN COMMUNITY IN TEXAS' GALVESTON BAY SYSTEM

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ABSTRACT

Between 1972 and 1978, changes in fish and crustacean populations of Cedar Bayou Electric Generating Station's cooling lake on upper Galveston Bay seemed related to rainfall rates during winter and spring. Wetter years favored populations of young migratory fishes and crustaceans; larger, predatory fishes tended to be more abundant during dry years than during wet years. This pattern is consistent with the hypothesis that part of the upper bay's value as nursery grounds derives from their low salinities which repulse larger fishes, thereby protecting juvenile organisms from intense predation. Dynamics of the cooling-lake community responded also to variation in the power plant's T (the difference between upper discharge-canal and intake-area temperatures) and to the occurrence of infrequent fish kills. A trend model of system dynamics was formulated and tested for internal consistency.

INTRODUCTION

Texas' coastal bays are used as nursery areas by many species of gulf fishes and invertebrates. The common life-cycle involves spawning by adults off-shore and subsequent movement of the young into the upper estuaries. In these low-salinity waters, food for young fish and crustaceans is abundant, predators are relatively scarce, and competition with adults is reduced. Gulfward movement, through waters with progressively higher salinity, occurs as the organisms grow or environmental conditions change (Gunter 1961).

The role of rainfall variation in productivity of the bays and lower estuaries has been stressed by numerous authors. Positive correlations between the commercial catch of white shrimp (Penaeus setiferus) and rainfall have been reported by Gunter and Hildebrand (1954) and by Viosca (1958). Positive correlations have been found also between freshwater inflow and white shrimp abundance in San Antonio Bay (Williamson 1977). Further, Chapman (1966), in an analysis of commercial harvest of estuary-dependent fishery resources from Texas waters (1956-1962), found that a series of wet years was about 41 percent more productive than a series of dry years. Rainfall and fishery production are linked presumably through salinity changes in the bays; however, the fertility of bays may also vary with rainfall production, being greater in wet years when inflow of nutrient-laden runoff is higher.

The objective of this study was to gain insight into the dynamics of fish and invertebrate populations in the upper Galveston Bay estuary. We felt that examination of population trends in an intensively monitored power-plant cooling lake over a period of several years might yield new information regarding estuarine productivity differences between wet and dry years.

STUDY AREA

Most data used in this study were collected as a part of a program to monitor ecological effects of the Cedar Bayou Electric Generating Station. This Houston Lighting & Power Company plant has three 750-MWe natural-gas fired units and uses a once-through cooling system.

Cooling water is drawn from Cedar Bayou at a rate of 25.3 X 10^4 m^3/hr when all units are operating. Cedar Bayou is a small coastal stream whose flow is dependent upon rainfall in the surrounding watershed. Because normal downstream flow is insufficient, except during floods, to supply the entire cooling-water requirement, the portion of Cedar Bayou downstream from the plant was dredged and widened to Tabbs Bay. Thus, the power plant's cooling water comes from two sources--upper Cedar Bayou, which delivers predominately fresh water, and lower Cedar Bayou, which contains higher salinity water (typically 2 to 15 ppt) from Tabbs Bay. On the average, about 70 percent of the cooling water pumped through the plant comes from lower Cedar Bayou. The cooling water transits a discharge canal (9.7 km long), then passes through a 1,053 ha cooling lake prior to entering Trinity Bay.

Water to be used for cooling passes through conventional traveling screens that have a 1-cm square mesh. These screens were revolved and backwashed approximately every 8 hours during the period when our data were collected. Impinged organisms, having been backwashed from the screens, are pumped into the discharge canal. Aquatic organisms' means of access to the cooling lake is to be either impinged or entrained and then passed down the discharge canal. A drop-structure prevents entry by fishes and crustaceans into the cooling lake from Trinity Bay, into which the effluent is ultimately discharged.

Landry (1977) found that at the P. H. Robinson Power Plant, another Houston Lighting & Power Company facility, fishes up to 30 mm standard length were most susceptible to entrainment while fishes from 30 to 120 mm were most susceptible to impingement. On the basis of Landry's results, we believe that only those fishes smaller than 120 mm standard length are likely to enter the cooling lake of Cedar Bayou Electric Generating Station.

The cooling lake is a variable place. That is, temperature and conductivity vary greatly within days, weeks, months, and years. Temperature (3° to 39°C) varies seasonally and with the operation of the power plant. Conductivity (1 to 30 mmhos/cm= 0-17 ppt) varies with rainfall and with the discharge of waste brine from the Barber's Hill Oil Field, which lies 32.3 km upstream on Cedar Bayou; the latter source of variation has become less important during recent years.

Substantial industrialization in the watershed contributes mostly unknown effects. Water from Tabbs Bay, which is 3 km from the Houston Ship Channel, sometimes contains abnormally high levels of industrial and domestic sewage (Metyko 1952; Carter 1970). In addition, upper Cedar Bayou receives effluents from petrochemical industries, municipal sewage, and runoff from agricultural and land-fill operations. A U. S. Steel plate mill discharges 4 to 6 million liters of waste-water per day into lower Cedar Bayou (Johnson 1973).

DATA SOURCES

Biological data for this analysis came from field studies by the senior author (unpublished), Jackson (1974), Eidman (1978), St. Clair (1978), and Pridgeon (1979, 1980). Fortunately, uniform methods were used throughout the 7-year monitoring program; each of us used identical stations and collecting gear. Sampling occurred at biweekly or monthly intervals. Biweekly sampling was adjusted to a monthly basis by taking the sample whose date was nearest to mid-month. Gear used for sampling were otter trawls and trammel nets. Six paired trawl and trammel-net stations were sampled. Trawl-hauls were 3 minutes in duration and trammel nets were fished for 10 minutes. All sampling was done at night.

Hydrological data were collected by Hammerschmidt (1973), Holt (1977), Chamberlain (1978), Jones (1977, 1978, 1979), and Ojeda (1980). Conductivity and temperature averages were calculated from daily readings. Rainfall and air-temperature data were taken from the National Climatic Center's summary reports for Texas (1972 to 1979). Commercial fishery-catch data were obtained from the annual summaries of Texas landings (National Marine Fisheries Service 1972 to 1978), which are tabulated by the Texas Parks and Wildlife Department. Data for 1979 were provided by James Morgan of the National Marine Fisheries Service.

ECOLOGICAL TRENDS IN CEDAR BAYOU

COOLING LAKE

In general, total numbers of fishes and crustaceans taken in the trawl during the 6-year period, 1973-1978 (only fall and winter data were available for 1972), followed similar trends (Figure 1A, 1B): Catches were greater during wetter years. This is what might have been expected, because smaller organisms that are susceptible to a trawl are also more likely to be tolerant of low salinities or even to be dependent upon them for their survival and well-being. Salinity/size relationships have been reported for various estuarine fishes by Weymouth, Linder, and Anderson (1933), and Gunter (1961); in general, larger individuals tend to occur at progressively higher salinities. Our trammel-net catches of larger fishes did not seem strongly related to annual rainfall (Figure 1C).

Annual average conductivity in the cooling lake was inversely related to the total rainfall for that year, during 1972 to 1978 (Figure 2A). There was no indication that wetter years were cooler; in fact, 1973 was both the wettest and warmest year (Figure 2B).

The cooling lake was constructed by flooding a subsiding salt marsh in May 1972. The initial fauna (Fall 1972-Summer 1973) was influenced by what was there to begin with and by what had managed to enter the lake via the power plant. During the first year, numbers of white shrimp (Penaeus setiferus), Atlantic croaker (Micropogon undulatus), and hardhead catfish (Arius felis) were high. Predatory and forage fishes were not abundant. Predatory fishes are here defined as large fishes that prey upon other fishes and macro-invertebrates; dominant predatory fishes in the cooling lake were spotted seatrout (Cynoscion nebulosus) and sand seatrout (Cynoscion arenaris). (Forage fishes are defined as small fishes that do not grow large, hence are subject to predation by larger fishes, and do not migrate long distances. They may reproduce in the cooling lake system; these were primarily bay anchovy, Anchoa mitchilli tidewater silverside, Menidia beryllina, and various members of Cyprinodontidae, Poeciliidae, and Gobiidae). Brown shrimp (Penaeus aztecus, blue crabs (Callinectes sapidus), and Gulf menhaden (Brevoortia patronus) were only moderately abundant relative to subsequent years. The cooling lake experienced a fish kill during December 1972.

During the second year (Fall 1973-Summer 1974), brown shrimp, Atlantic croaker, blue crabs, and forage fish increased while hardhead catfish and white shrimp populations declined. Predator populations remained low. Another fish kill was observed in December 1973.

During the third year (Fall 1974-Summer 1975), initial testing of the third generating unit and other plant operations resulted in lowest values of T (the difference between upper discharge-canal and intake-area temperatures) recorded during the study (6.1°C in fall and 5.3°C in spring). Conspicuously, brown shrimp, blue crabs, and menhaden obtained their peak numbers during this year. Larger numbers of predators appeared in the trammel net. Catches of white shrimp and forage fishes increased while croaker catches declined. Hardhead catfish hit their 7-year low.

During the fourth year (Fall 1975-Summer 1976), another fish kill occurred in December. Predator and menhaden catches declined drastically, while catches of brown shrimp, croaker, and blue crabs declined to a lesser extent (probably the predators were most affected by the fish kills). White shrimp and forage fishes achieved noticeable peaks. Hardhead catfish began increasing in numbers.

During the fifth year (Fall 1976-Summer 1977), numbers of predators and hardhead catfish increased while catches of white shrimp, forage fishes, blue crabs, croaker, menhaden, and brown shrimp declined.

In the sixth year (Fall 1977-Summer 1978), predators and hardhead catfish obtained their 7-year highs, while croaker, blue crabs, white shrimp, and menhaden fell to their 7-year lows. Forage-fish catches were at their lowest levels since the cooling lake's first year. Brown shrimp declined. Total rainfall during 1977 was the lowest since 1969; conductivity remained high into the first half of 1978. Average T of the Power plant reached its 7-year high in summer 1978 (10.9°C).

In the seventh year (Fall 1979-Summer 1979, hardhead catfish remained numerous while predators declined. Forage fish, menhaden, croaker, blue crabs, and white shrimp increased. Brown shrimp declined to their 7-year low. Rainfall was high, conductivity was low.

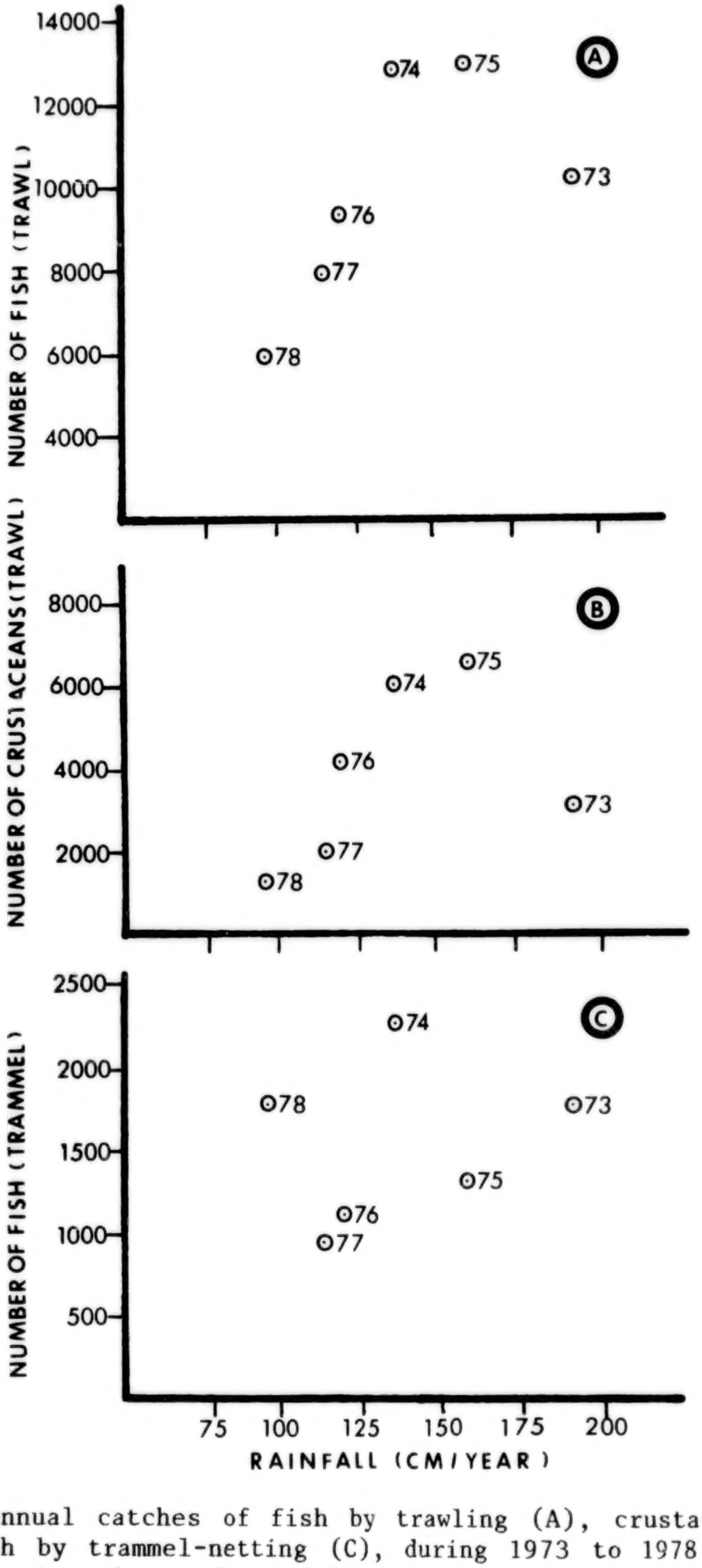

Figure 1. Annual catches of fish by trawling (A), crustaceans by trawling (B), and fish by trammel-netting (C), during 1973 to 1978 from the cooling lake as a function of annual rainfall.

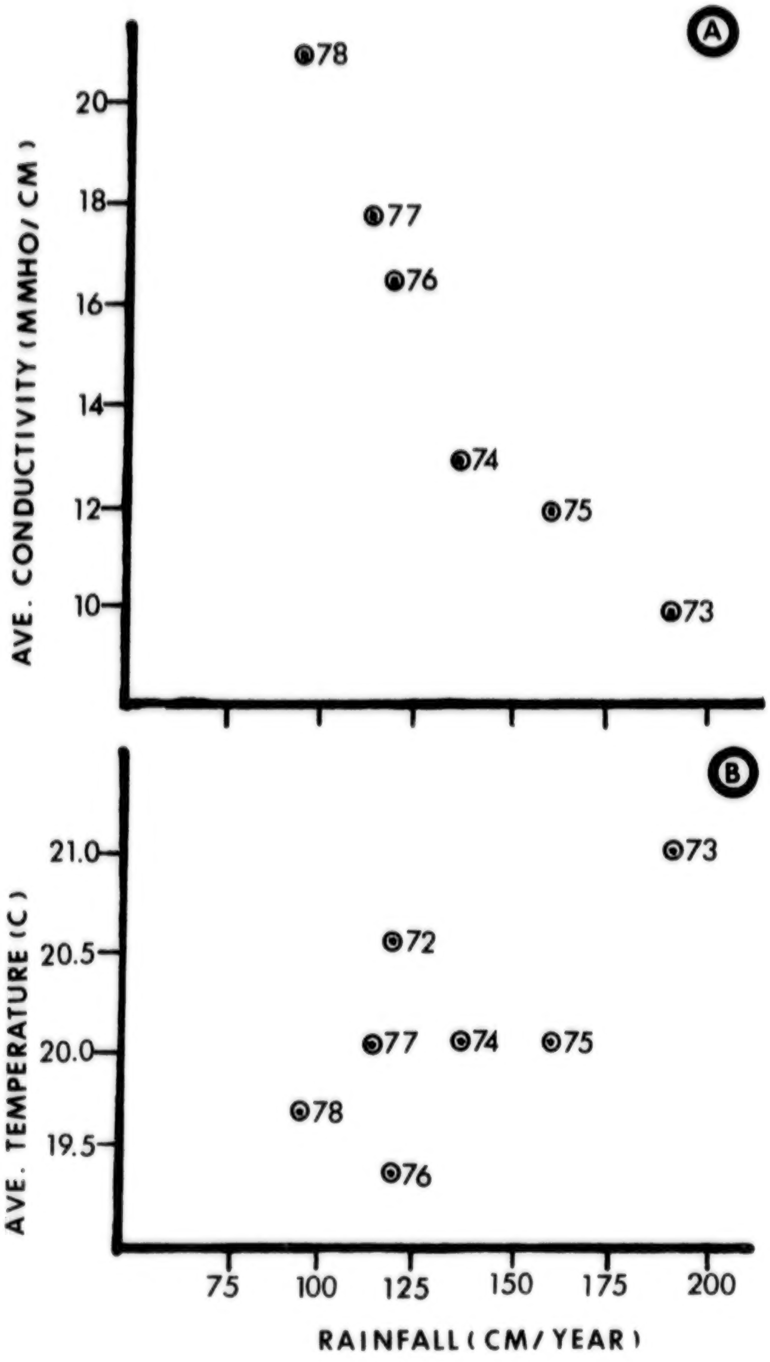

Figure 2. Annual averages of conductivity in the cooling lake (A) and air temperature (B) during 1973 to 1978 as a function of annual rainfall.

A TREND MODEL AND ITS STATISTICAL INTEGRITY

The above relations were formed into a conceptual model of cooling-lake dynamics (Figure 3). In our view, the principal response sequence and its ecological basis are as follows: (1) Rainfall during the winter-spring inversely affects the cooling lake's salinity. (2) If winter-spring rainfall is low, cooling-lake salinity remains at relatively high levels, which favors overwintering predatory fish (Figure 4); otherwise, salinity declines to levels that are stressful to predatory fishes, perhaps causing them to emigrate from the lake. (3) Large numbers of predatory fishes overwintering in the lake during relatively dry years consume croaker, forage fishes, menhaden, shrimps, and crabs in numbers sufficient to reduce populations of these forms. (4) Populations of brown shrimp, blue crab, forage fishes, and menhaden respond inversely to T of the power plant. Large Ts increase mortality rates among entrained and impinged organisms, thus reducing their recruitment to the cooling lake. Heat killed and disabled organisms entering the cooling lake are consumed by such facultative scavengers as hardhead catfish, which consequently benefit from higher Ts. The trend toward increased Ts since 1974 parallels a progressive increase in the volume-flow of water through the cooling system. Therefore, some T-correlated biotic responses may reflect gradually increasing lake temperatures rather than increasing T *per se*. (5) Croaker and hardhead catfish populations interact during winter-spring, resulting in an inverse relationship between their population densities (Figure 5). Hardhead catfish are favored over croaker during dry winters in which croaker are subject to intense predation. Normally, hardhead catfish do not overwinter in Texas' upper estuaries; hardhead catfish do remain in the cooling lake, presumably because temperatures become unfavorable in the downstream portion before further decline of temperature would otherwise induce imigration from the warmer, receiving end of the cooling lake. Thus, hardheads are trapped at the warm end of thermal gradient and so must overwinter in the cooling lake. (6) The size of croaker populations in the cooling lake during winter-spring depends partly upon Galveston Bay system's spawning stock, the size of which is reflected by commercial catch rates of croaker during the previous year (Figure 6). (7) Events related or unrelated to rainfall occasionally result in winter-kill of predatory fishes in the cooling lake; populations of prey organisms are largest during winter-spring periods that follow early winter-kills.

Internal consistency of the model is indicated by the extent to which hypothesized relationships among variables (rainfall, 1/conductivity, 1/T, 1/predator, croaker, forage fish, white shrimp, 1/hardhead, blue crab, brown shrimp, and menhaden) were concordant (Figure 7). Over all variables (11) and years (7), Kendall's coefficient of concordance was 0.36 ($p < 0.01$; see Siegel 1956). When the model was reduced by deleting one variable (from most concordant to least concordant with trend of the other variables):

1. hardheads; blue crabs
2. T; menhaden; croaker
3. brown shrimp; white shrimp

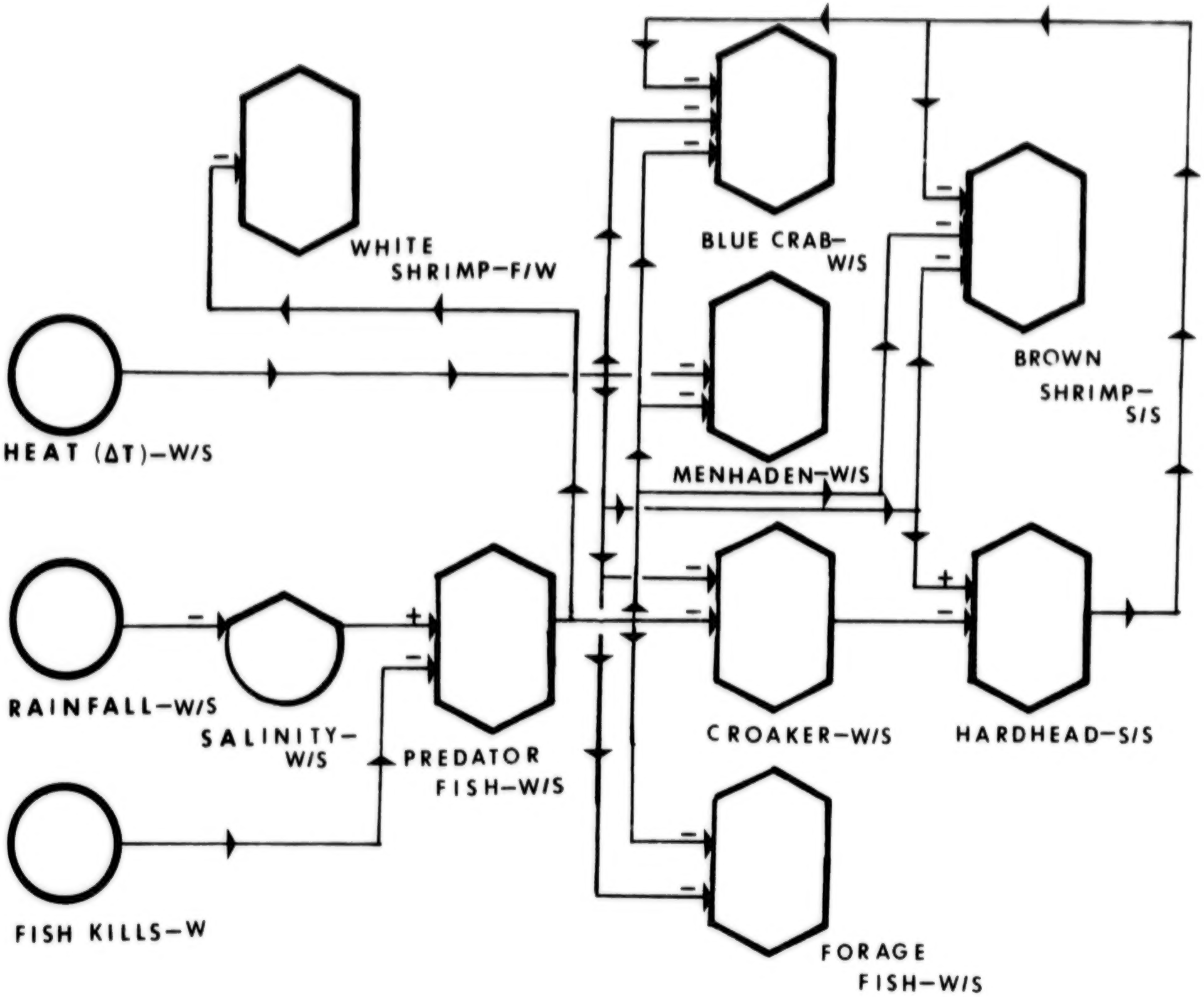

Figure 3. Conceptual model of relations among driving variables and biotic responses in the cooling lake. A "plus" symbol indicates direct proportionality; a "minus" symbol, inverse proportionality. F/W = fall and succeding winter; W/S = winter and succeeding spring; S/S = spring and succeeding summer.

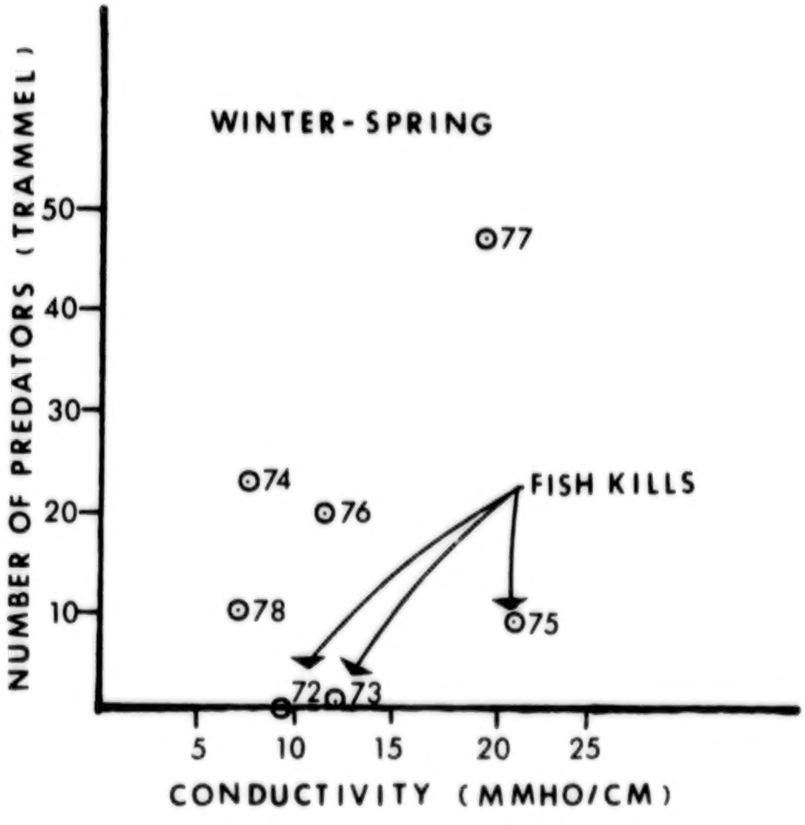

Figure 4. Trammel net catches of predatory fishes from the cooling lake versus average conductivity during winter-spring, 1972 to 1978. Note the relatively small catches of predatory fishes following December fish kills in 1972, 1973, and 1975.

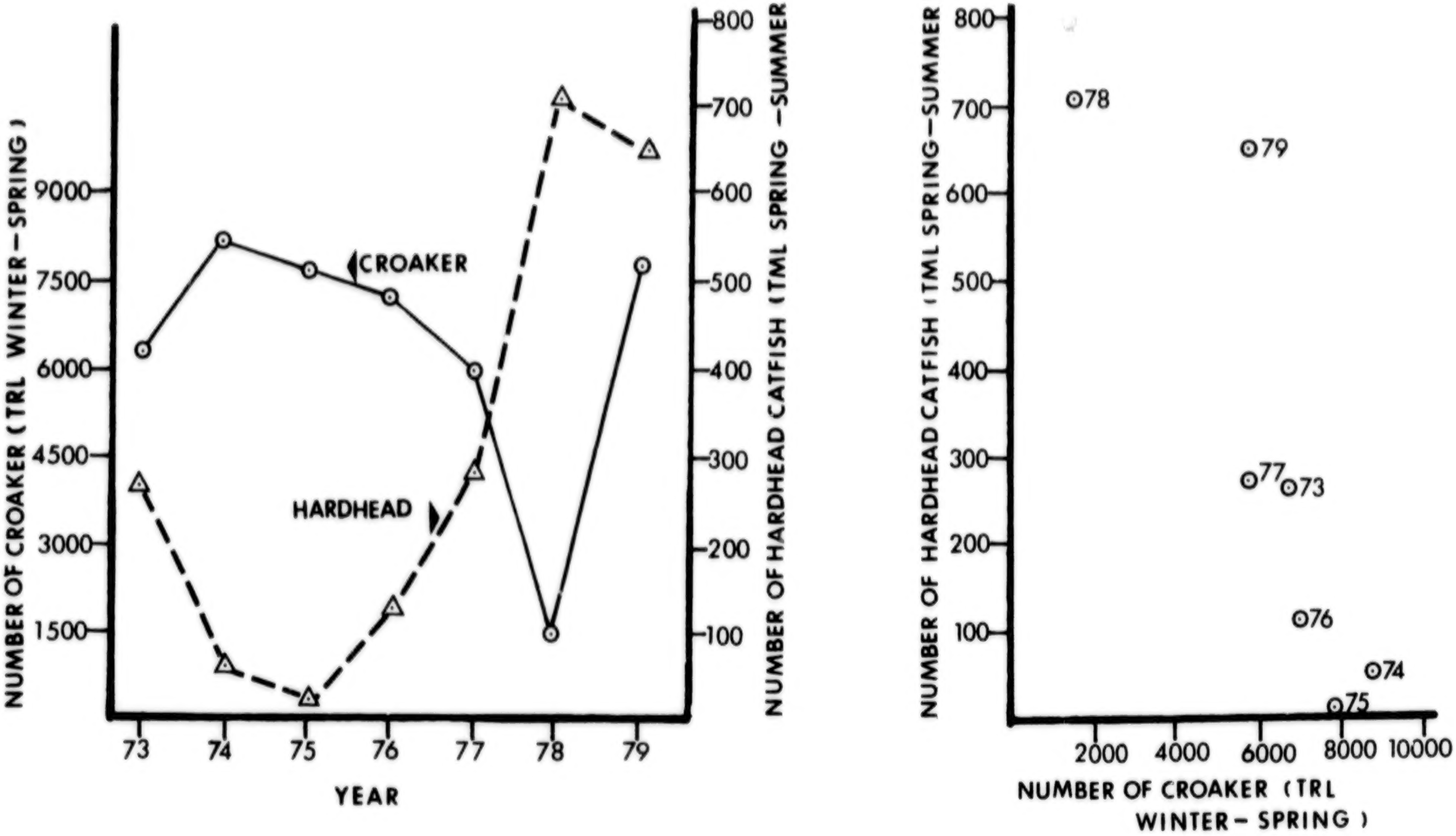

Figure 5. Inverse relation of winter-spring catch of croaker by trawling to spring-summer catch of hardhead catfish by trammel-netting, 1973-1979, from the cooling lake.

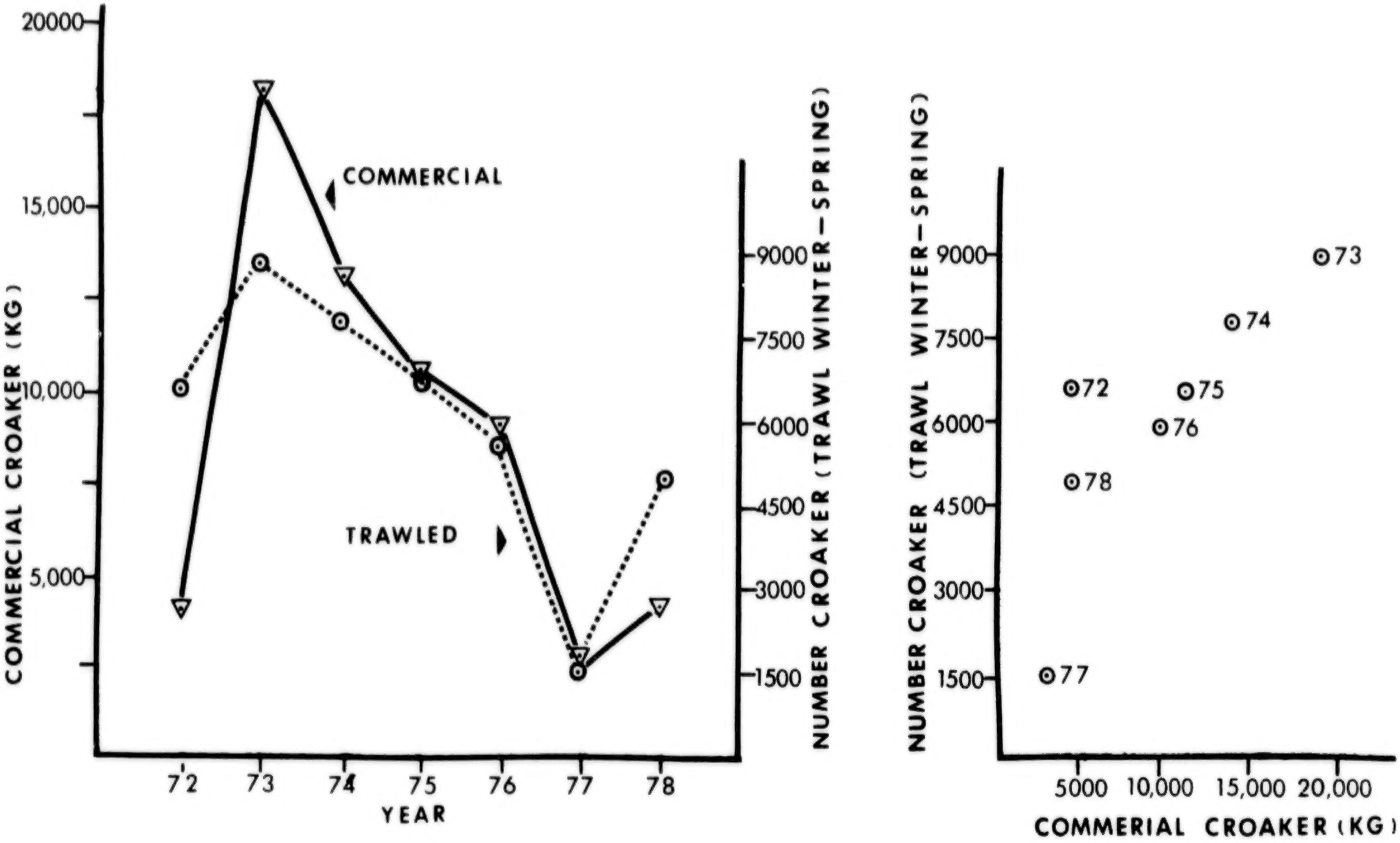

Figure 6. Relation of annual commercial catch of croaker from Galveston Bay with the trawled catch of croaker from the cooling lake during the succeeding winter-spring.

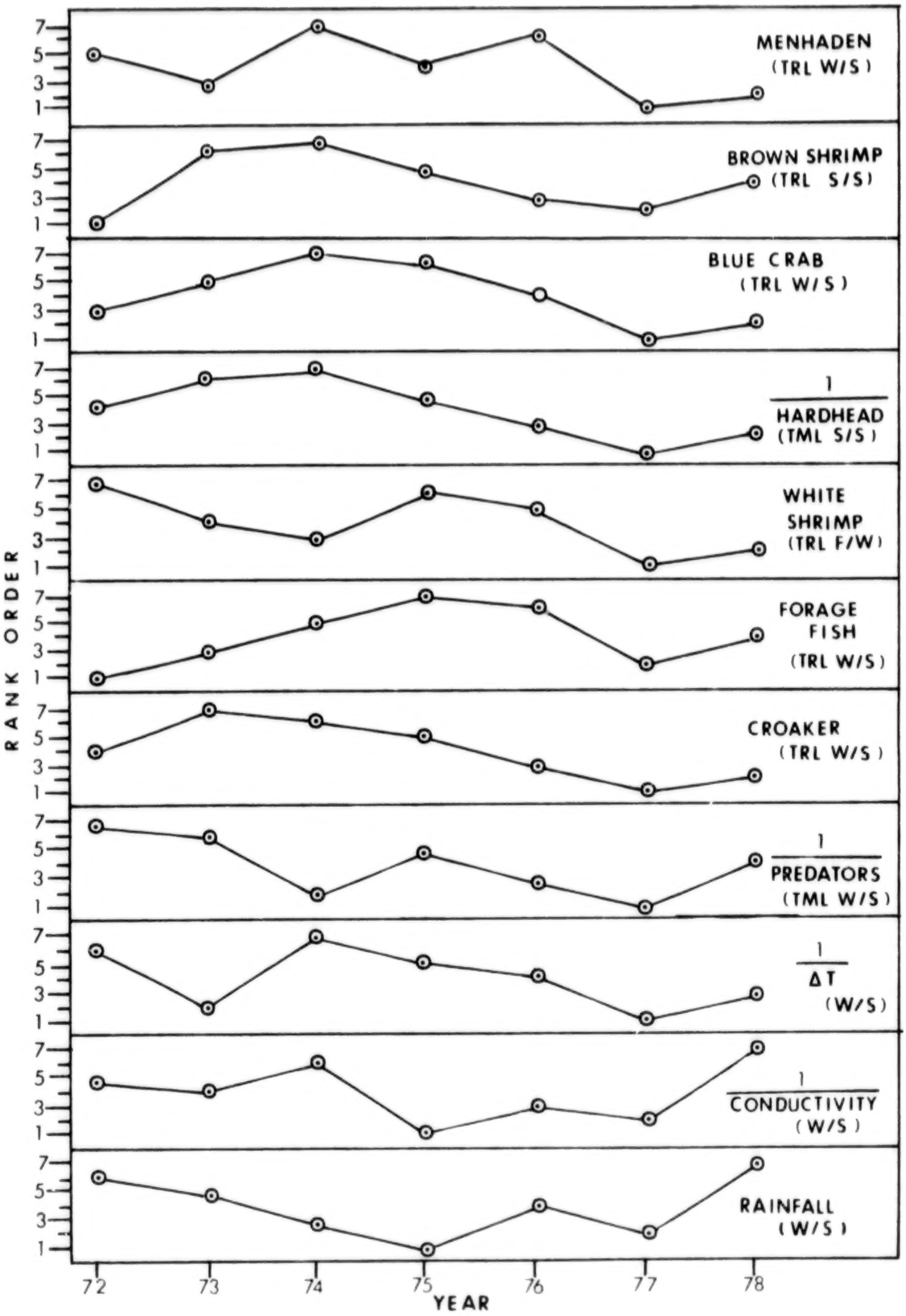

Figure 7. For each component of the cooling lake model (Figure 3), the ranked value during 1972-1978. Components that, under the model, are inversely related to rainfall are represented by their reciprocals. Were the model completely concordant, all "graphs" would be identical. F/W = fall and succeeding winter; W/S = winter and succeeding spring; S/S = spring and succeeding summer.

4. predators
5. forage fish
6. conductivity
7. rainfall

Thus, the most concordant variables were T and associated biotic variables (hardheads, blue crabs, croaker, menhaden), while the least concordant were those associated with rainfall and conductivity (predators) and those biota whose numbers were low during initial lake operation (predators and forage fish), and those most affected by fish kills (predators).

Eliminating conductivity and rainfall from the model increased Kendall's coefficient from 0.36 to 0.52. Eliminating T lowered the coefficient to 0.34. Elimination of all three forcing variables increased the coefficient to 0.67, indicating greater agreement among biotic elements than for the model as a whole. This result was to be expected because part of the cooling-lake fauna seems to be influenced by T and the other part seems driven by salinity/predator interactions. Moreover, biotic responses reflect the operation of many environmental variables not included in the model.

When the model was reduced by deleting one year at a time, years ranked as follows (from most to least concordant):

1. 1977
2. 1974
3. 1976; 1978
4. 1973
5. 1975
6. 1972

The least concordant year was the cooling lake's initial year. The two most concordant years were those with high numbers of predatory fishes. The three years having the least concordance were the ones which had reported fish kills. When the model was reduced by deleting the three least concordant years, Kendall's coefficient went from 0.36 to 0.60.

CONCLUSION

Our analysis has uncovered ecologically interpretable patterns in the changing structure of a Texas estuarine community. While these patterns seem reasonably related to temporal variation in watershed rainfall and consequent variation in habitat-salinity, complexity is added by the selective filtering action of a steam-electric power plant through which all immigrants to the community must pass.

ACKNOWLEDGMENT

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HISTORICAL OVERVIEW OF THE FRESHWATER INFLOW AND SEWAGE TREATMENT PLANT DISCHARGES TO THE POTOMAC RIVER ESTUARY WITH RESULTANT NUTRIENT AND WATER QUALITY TRENDS

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ABSTRACT

Nitrogen, phosphorus and carbon loadings in the estuary have increased since the early 1920's. Algal and plant vegetation have undergone three major population and community shifts during the period of increased nutrient loading. Carbon loadings began to decline in the late 1950's with phosphorus decreasing in 1970. Nitrogen loadings have remained elevated with a small decline in the mid-70's. Extensive wastewater phosphate removal processes were initiated in 1974. During the summer of 1977 (a below-average flow period), the maximum was 80 µg/l for a 14-km reach of the estuary. The algal populations in 1979 were mixed, indicating that the water quality in the upper estuary is improving due to phosphorus being reduced by extensive removal from wastewater discharges. The Potomac River Estuary received in 1980 approximately $1.7 \times 10^{+9}$ liters/day (460 mgd) of wastewater discharges from 8 sewage treatment plants in the upper estuary, which during low flow periods contribute significantly to the freshwater flow into the estuary.

INTRODUCTION

The "Clean Water Act" (P.L. 92-500), entitled "The Federal Water Pollution Control Act Amendments of 1972," affirms the biological integrity of the Nation's waters. This objective, which is seemingly simple and precise, nevertheless presents a complex challenge of surprising magnitude when applied to the real world. The absence of an environmental awareness during decades of industrial and urban/suburban development has exacted a heavy toll that is evident today in our diminished quality of life and our dwindling natural resources. An historical perspective of the events which have influenced the ecological health of the Potomac Estuary is presented in Table 1.

Numerous technical studies have been conducted and reports written about the water qualty of the estuary. Most of them deal with a short-term perspective of the changes taking place therein. Questions relating to cost-effectiveness of alternative treatment control processes and the benefits to the ecology of the

Table 1. Historical perspective.

1608	Captain John Smith describes the Potomac as "fed with many small rivers and springs, frequented by otters, beavers, martins, and sables. Neither better fish, more plenty, nor more variety for small fish had any of us ever seen in a place."
1730	The lower Potomoc carries a great deal of commerce of tobacco, shad, herring and lumber.
1787	The Potomac River Fisheries Compact is signed, which guarantees equal fishing rights to Virginia and Maryland but gives ownership of the river to Maryland.
1790	Vice-President Adams swims daily in the Potomac Estuary.
1842	The Baltimore and Ohio Railroad is completed, which discharges raw wastes from its passenger cars into the Potomac at bridges.
1860	President Lincoln is forced to vacate the White House on some late summer nights due to the odor of the Potomac (presumably raw sewage or a local blue-green algal bloom).
1863	Beginning of public water supply in Washington, D.C.
1870	Untreated human wastes are carried into the river by eight miles of sewers and culverts.
1886	Microbiologist W.K. Brooks conducts first biological study of Potomac River (primarily of Chesapeake Bay).
1889	A group of engineers is appointed by President Benjamin Harrison to find a better sewage disposal system.
1894	The Public Health Service reports that the Potomac is so loaded with sediment and fecal bacilli at certain times of the year that it is unfit for bathing, cooking, or drinking.
1912	First biota data collected (by Abel Wolman and others) on the Potomac River (Potomac River Survey, U.S.P.H.S.). Very heavy algal growth on mud flats below Washington considered as valuable purification mechanisms by Professor Phelps. The population of Washington now exceeds 300,000.
1920	Officials agree that Washington's sewage should be treated before it is discharged into the Potomac.
1920	Water chestnut invasion begins. Eventually it reaches proportions where the Army Corps of Engineers have to initiate a mechanical removal project to unclog areas for navigation.

Table 1. Continued

1938	The Blue Plains Sewage Treatment Plant begins operation, but provides only primary treatment.
1940	The Interstate Commission on the Potomac River Basin is formed and given the task of monitoring water quality and activities which affect it throughout the basin.
1948	Water milfoil (*Myriophyllum spicatum*) replaces water chestnut in many areas and nuisance conditions develop.
1957	First Potomac Enforcement Conference, recommended upgrading existing sewage treatment plants.
1959	Secondary sewage treatment is added at Blue Plains and consists of aeration, filtration, and chemical treatment.
1965	The Water Quality Act, which first set certain required water quality standards, is passed.
1966	Water milfoil disappears suddenly.
1967 to 1970	Blue-green algae, especially *Anacystis*, *Anabaena*, and *Osicillatoria*, dominate milfoil and chestnut are still present but not dominant.
1968	Chlorination is initiated on the effluent of sewage treatment plants in the Washington area.
1969	Second Potomac Enforcement Conference held. An official from the Federal Water Pollution Control Administration described the river as "a severe threat to the health of anyone coming in contact with it" because of bacterial contamination. Raw solid sewage can be seen floating on the surface after rains and fish kills related to low dissolved oxygen occur.
1969	Recommendation from the Potomac Enforcement Technical Advisory Committee and Assistant Secretary of Interior. Initiation of water quality studies by the Chesapeake Technical Support Laboratory (CTSL) which is now the EPA Central Regional Laboratory.
1970	As a result of the second conference, a Memorandum of Understanding was adopted between D.C., MD., and VA. which formalized water quality requirements and goals.
1970	The Environmental Protection Agency (EPA) is established, taking responsibility over water-quality improvement programs.
1971	The D.C. Health Department prohibits recreation of swimming in the Potomac, Rock Creek, and Anacostia River.

Table 1. Concluded

1972	The "Georgetown Gap", a storm drainage outlet which sometimes pours 25 million gallons of raw sewage daily into the Potomac, is closed.
1972	P.L. 92-500 the Federal Water Pollution Control Act Amendments ("The Clean Water Act") enacted by Congress.
1974	Blue Plains begins trial program of phosphorus removal from waste water discharges (both alum and ferric chloride).
1975	Chlorination has reduced bacteria counts, but problems remain with algal blooms, sediment, and low dissolved oxygen (DO).
1976	Arsenic from a chemical plant in Alexandria is discovered in the Potomac.
1977	Blue Plains improves secondary treatment facilities and reduces the volume of pollutants entering the Potomac.
1979	First primary productivity versus light (irradiance) penetration (spectral distribution-quantitative and qualitative) studies.
1980	Advanced wastewater treatment is scheduled to begin with the completion of the new Blue Plains facility, which will remove over 80 to 85% of the phosphorus from the effluent. In July, nitrification (removal of nitrogenous oxygen demand) 50% operational with full plant operational by October.
1981	Multi-media filter system scheduled to be operational at Blue Plains in June.

Adapted from "Clean-up Chronology" by the Interstate Commission on the Potomac River Basin and other sources, Washington Post, November 10, 1977.

estuary resulting from these programs are difficult to address. In many cases, the data are not available to adequately assess these issues, or wastewater control processes have not been in place long enough to determine any cause-and-effect relationship, beneficial or otherwise. This paper attempts to review the wastewater loadings to the Potomac River Estuary from 1913 to 1980 with emphasis on water quality in the past decade during which major wastewater control processes were implemented.

DESCRIPTION OF STUDY AREA

The Potomac River Basin is the second largest watershed in the Middle Atlantic States. It flows through four states (West Virginia, Pennsylvania, Virginia, and Maryland) and has a combined drainage area of 38,000 km^2 (14,670 mi^2). The river is about 544 km (400 mi) long. The Potomac River Estuary is the last 182 km (114 mi) of the main stem of the Potomac River, from the furthest extent of the tidal influence near Chain Bridge (the Fall Line, which is just above Washington, D.C.) to its confluence with the Chesapeake Bay at Point Lookout (Figure 1). The mouth of the estuary is 9.65 km (6.0 mi) wide at Point Lookout and decreases gradually to less than 0.8 km (0.5 mi) through Washington, D.C. The maximum depth is 32.6 m (107 ft). The U.S. Army Corps of Engineers has in the past maintained a navigable channel that is 7.3 m (24 ft) deep from the mouth of the estuary to Washington, D.C. However, extensive dredging has not taken place since the mid-1960's due mainly to the lack of suitable dredge material disposal sites. The mean tidal range is about 0.9 m (2.9 ft) near Washington and about 0.4 m (1.4 ft) near the Chesapeake Bay. The lag time for the tidal phase between Washington and the Chesapeake Bay is about 6.5 hours (Jaworski et al. 1971; Mason and Flynn 1976; Champ et al. 1978; Lippson et al. 1979).

The Potomac ranks eighth among Atlantic seaboard rivers in average daily discharge, having an average freshwater inflow to the estuary of 314 m^3/s (11,100 ft^3/s). The maximum and minimum flows on record are 13,700 m^3/s (484,000 ft^3/s), observed in 1936, and 17.0 m^3/s (600 ft^3/s), observed in 1966. In comparison, the maximum flow recorded during Tropical Storm Agnes in 1972 was 10,167 m^3/s (359,000 ft^3/s).

The Potomac River Estuary is delineated geographically by the extent of tidal influence (ebbing and flooding). The estuary is divided into three reaches on the basis of salinity, as shown in Figure 1 (from Pfitzenmeyer 1976). Chain Bridge is commonly used as the reference point for the upstream boundary, even though this boundary in reality is Little Falls. (See Chart 1).

CHART 1

Reach	Description	River Kilometers
I. Tidal Freshwater (Limnetic 0.5 ppt)	Chain Bridge to Quantico	211-124 (87)
II. Mixing Zone (Oligohaline 0.5-5.0 ppt)	Quantico to Morgantown	124-87 (37)
III. Estuarine (Mesohaline 5-18 ppt)	Morgantown to Chesapeake Bay	87-0.0 (87)

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ppt = part per thousand

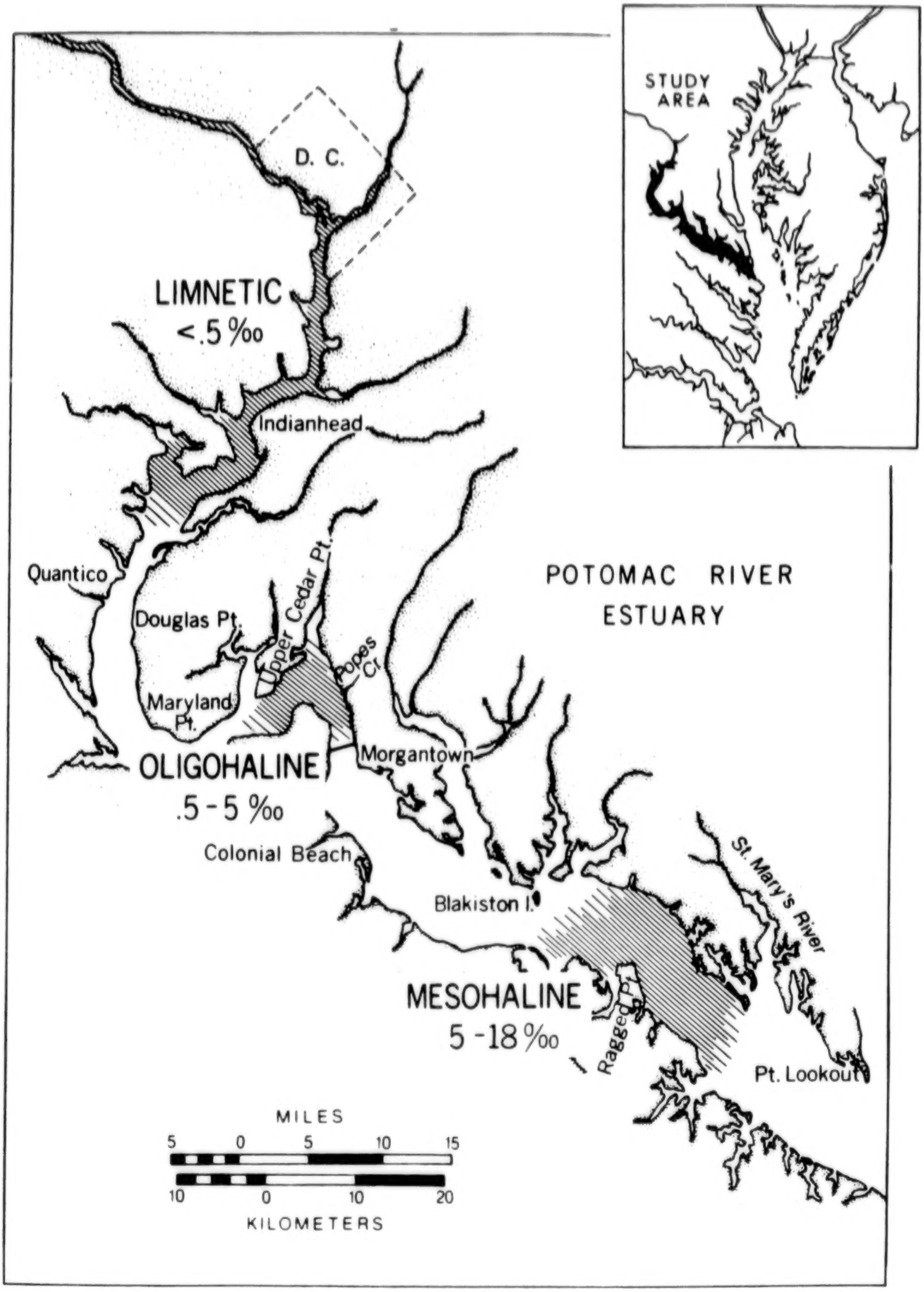

Figure 1. The Potomac River Estuary with the three perpetual salinity zones indicated.

These three salinity zones differ markedly in their physical and chemical characteristics and in their abilities to sustain various biological communities. In this sense salinity is one of the most important factors affecting aquatic life. The upper reach is primarily a freshwater zone containing spawning and nursing areas for anadromous fish and is noted for high phytoplankton and zooplankton productivity. This tidal freshwater reach is impacted by major municipal wastewater discharges which from 1979 to 1980 had a combined average waste flow of approximately 20.2 m^3/s (460 mgd), (Villa in preparation).

The second reach, which is 32.2 km (20 mi), is the mixing zone. This is a low, brackish, or oligohaline zone where salinity is highly variable and is dependent on the season, the point in the tidal cycle, and the depth. Salinity may vary as much as 7 ppt over the water column depending on the season and forage fish populations, and moderate phytoplankton and zooplankton productivity.

The lower reach is a 75.6-km (47-mi) stretch which has an average salinity of 12 ppt (ranging from 5 to 18 ppt). Within this reach are large forage fish populations, predator fishes, blue crabs, oysters, and clams.

MORPHOMETRY

The basic morphometric data for the three reaches of the Potomac Estuary (Jaworski 1977) are tabulated in Chart 2. Because of tidal action and low salinity, the upper reach is unstratified. Stratification begins in the middle reach during summer conditions. In the lower reach, stratification occurs mostly during summer conditions.

Chart 2

	Upper	Middle	Lower
Length (km)	87	37	87
Avg. depth (m)	4.8	5.1	7.2
Avg. width (m)	1100	3625	9740
Surface area (m^2 x 10^6	57.4	211.6	695.2
Volume (m^3 x 10^7	26.4	102.5	496.5

HYDROLOGY

The mean monthly flows of the Potomac at Little Falls (station No. 01646502) are tabulated below for the reference period of 1931 to 1980 (USGS-Towson, MD). These have been adjusted for riverflow diverted (just below Little Falls) for water supply (See Chart 3).

Tides dominate the currents in the Estuary. Typical miximum tidal velocities (Jaworski 1977) for the three reaches are:

Reach	Velocity (cm/sec)
Upper	25
Middle	28
Lower	18

The hydraulic detention time for any given reach of the tidal system depends on the rate of freshwater inflow. The water renewal time for the three reaches (Jaworski 1977) are given in Chart 4 for the 5, 50, and 95 percent flow conditions. This tabulation indicates that the upper reach has relatively short detention times, while the lower reach has times similar to that of most lakes.

The upper Potomac River Basin is the major source of freshwater inflow into the estuary. From 1930 to 1968, the average flow at Little Falls was 317 m^3/s (11,190 ft^3/s), or 7,234 mgd before diversions for municipal water supply. Table 2 presents mean yearly discharges (Jan.-Dec.) into the upper Potomac River estuary for 1931-1980.

Chart 3

Mean Monthly Flow (m^3/sec)	
January	397
February	375
March	667
April	562
May	413
June	263

Mean Monthly Flow (m^3/sec)	
July	145
August	154
September	141
October	219
November	200
December	305

Chart 4

Flow	Percent of time	Hydraulic	Detention	Time	(years)
(m^3/sec)	flow exceeded	Upper	Middle	Lower	Total
40	95%	0.21	0.81	3.95	4.07
185	50%	0.045	0.175	0.854	1.07
1150	5%	0.0073	0.028	0.137	0.17

Table 2. Mean yearly river discharges* (Jan. - Dec.) in m^3/s into the headwaters of the Potomac River Estuary for 1931-1980.

Year	m^3/s	Year	m^3/s
1931	170	1958	337
1932	309	1959	193
1933	380	1960	314
1934	227	1961	351
1935	334	1962	309
1936	453	1963	235
1937	518	1964	278
1938	204	1965	238
1939	303	1966	201
1940	354	1967	320
1941	198	1968	258
1942	405	1969	156
1943	309	1970	357
1944	272	1971	411
1945	343	1972	609
1946	258	1973	425
1947	198	1974	300
1948	368	1975	453
1949	388	1976	348
1950	380	1977	266
1951	362	1978	412
1952	445	1979	593
1953	331	1980	327
1954	215		
1955	326		
1956	292		
1957	255		

Sources: USGS Annual Water Year Reports, Water Resources Data for Maryland and Delaware.

*USGS Station 1646500 near Washington, D.C. (Little Falls - 1.2 mi [1.9 km] upstream form Chain Bridge, adjusted for amounts diverted for municipal use).

Table 3. Total estimated wastewater loading trend for upper Potomac River Estuary (from the greater Washington, D.C. area) for indicated years and parameters.

Year	Population ($x10^6$)	Wastewater Flow (m^3/s)	BOD_5 (MT/day)	TN (MT/day)	TP (MT/day)
1913	0.3	1.8	26.3	2.9	0.5
1932	0.6	3.9	46.7	5.2	0.9
1944	1.2	7.3	64.0	10.4	1.8
1954	1.4	8.5	90.7	14.4	2.5
1957	1.7	9.2	92.5	15.2	2.9
1960	1.9	9.7	50.0	16.9	4.5
1965	2.1	13.4	56.7	19.0	8.5
1968	2.4	14.0	59.0	22.7	9.1
1969	2.5	14.0	58.5	25.0	9.6
1970	2.5	14.1	64.0	27.2	10.9

Parameter	1968	1970	1977	1978	1979
Wastewater Flow (m^3/s)	14.0	14.1	15.8	17.7	18.8
BOD_5 (MT/day)	61.7	64.0	33.8	40.8	29.9
TOC (MT/day)	45.4	45.4	37.2	26.3	25.0
TKN (MT/day)	25.0	27.2	22.2	23.6	21.8
NH_3 (MT/day)	18.6*	18.7	19.5	21.3	20.4
NO_2 + NOS_3 (MT/day)	1.7	1.7	0.8	1.1	1.0
TPO_4 (MT/day)	32.2		10.0	7.7	
Pi as PO_4 (MT/day)	20.9		7.3	4.5	
Inorg Ni Inorg P Ratio's (by Atoms)	6.8:1	20:1	34:1		

MT = Metric tons (tonnes)

Sources: EPA (1969, 1970), Clark and Roesch (1978), EPA Water Quality Data Sheets, Central Regional Laboratory and EPA STORET.

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* Estimated as 75% of TKN (based on other historical data).

** Estimated as 65% of TPO_4 (based on other historical data).

NUTRIENT SOURCES

Four nutrient sources dominate nutrient loading into the estuary: (1) wastewater discharges (STP-point source), (2) upriver nutrient load, (3) urban/suburban runoff (storm, and combined sewer overflows and non-point sources), and (4) biochemical and chemical processes. Depending on river flow, turbidity, and water temperature, any one of these sources can be dominant and can vary both temporally and spatially.

In an estuary the temporal and spatial changes which occur in the plant and algal community are influenced by physical, chemical, and biological factors. The most influential physical and chemical factors include light (spectral distribution), salinity, and nutrient levels. Zooplankton predation is the dominant biological factor which affects the diversity and abundance of the phytoplankton community (Fogg et al. 1973). In order to understand the complex interrelationships and the nature of eutrophication in the Potomac River Estuary, one must be able to delineate the physical, chemical, and biological factors which are involved in the production and reduction of organic matter. Champ (1975) defined eutrophication as "the build-up of rapidly cycled organic matter" in which photosynthesis, respiration, and mineralization are complex processes that affect the overall health of a body of water in critical ways. The processes of production and reduction of organic matter can also at times dominate water quality parameters in the Potomac Estuary (BOD, pH, algal and bacterial biomass, etc.).

WASTEWATER ENRICHMENT

TRENDS (1913-1980)

In the Potomac River Estuary, wastewater discharges have resulted in an overall degradation of water quality characterized by increased nutrient levels and major shifts in submerged plant and algal populations, (See Figure 2, modified by Jaworski et al. 1971). Since the 1980's, the degraded water quality has resulted in a series of nuisance plant infestations Bartsch 1954; Stoffs and Longwell 1962; Jaworski et al. 1969; Pheiffer 1976). The early plant community was dominated by water chestnut, which presented a problem by clogging the tributaries of the upper estuary. In the 1940's and 1950's, an extensive invasion of Eurasian water milfoil (Myriophyllum spicatum) and a small incidence of blue-green algae replaced water chestnut as the dominant nuisance plants. During the 1950's and 1960's, the estuary was characterized by massive blooms of blue-green algae which were dominated by Anacystis cyanea. These blooms continued until 1977, when Pseudo anabaena catenata replaced Ana cysitis as the dominant species of undesirable blue-green algae (Clark et al. 1980). During 1978 to 1980, there was increased algal diversity with smaller isolated blue-green algal blooms of short duration.

Wastewater nutrient enrichment trends for carbon, nitrogen, and phosphorus from 1913 to 1980 are plotted in Figure 2. Overlaid on the same axis are the major shifts in submerged plant and algal populations. The nutrient enrichment trend

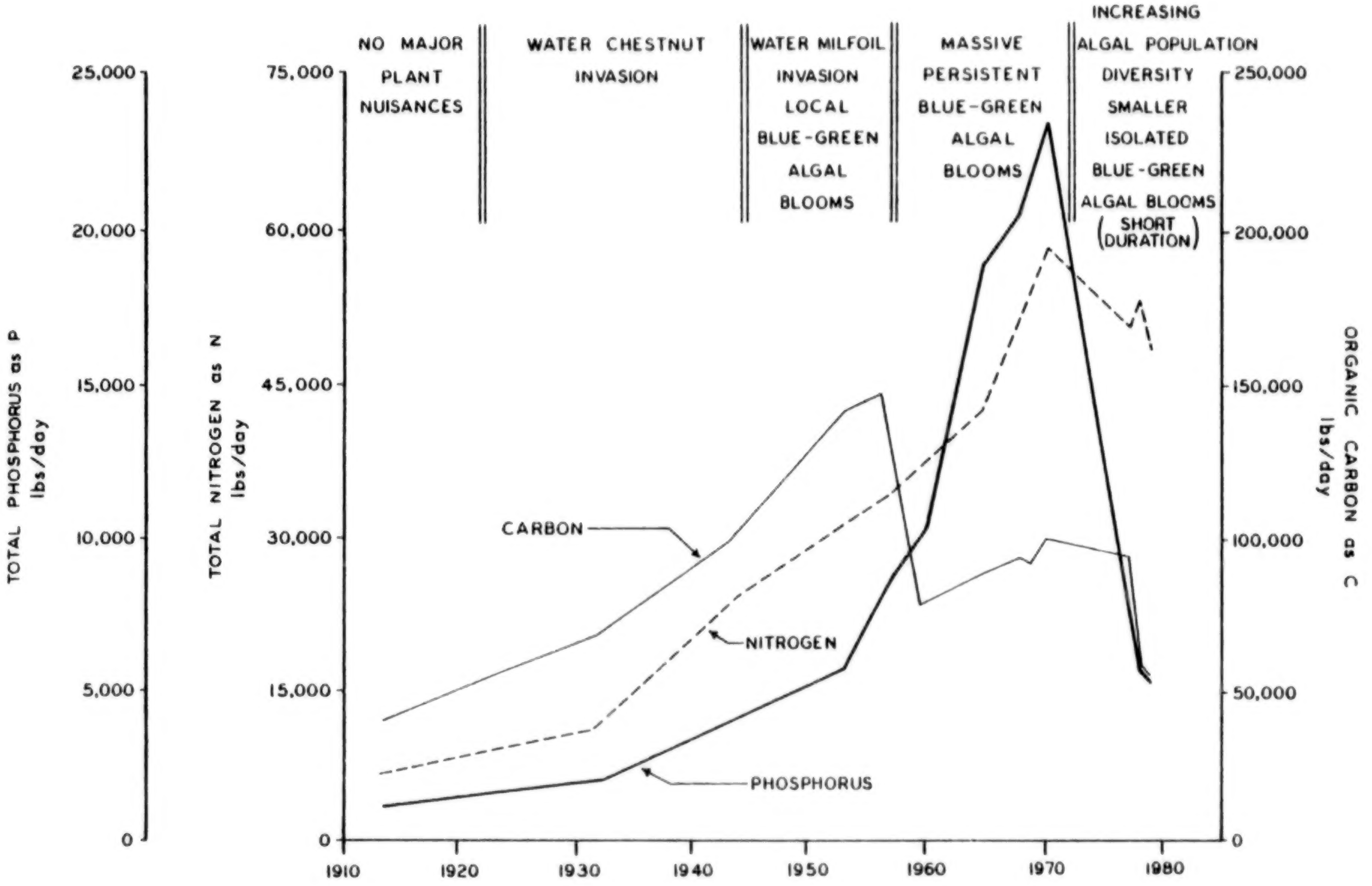


Figure 2. Wastewater nutrient enrichment trends and ecological effects in the upper Potomac River Estuary.

appears to have an ecologically significant correlation with the development and alteration of dominant plant and algal populations, which could be characterized as the stages of eutrophication for the Potomac River Estuary. However, field and laboratory data are available only for the correction of blue-green algal blooms subsequent to nutrient enrichment. Similar data are scarce for correlation with the invasion and disappearance of major submerged aquatic plants. The shift here is probably nutrient driven (with each successive species more adapted to, tolerant of, or competitive with nutrient enrichment); however, the sharp decline of these submerged aquatic plants could also be attributed to increased turbidity in the water column or an unknown plant disease (virus, as proposed by Bayley et al. (1968). Therefore, data are not available to substantiate our belief that these plant and algal responses are really aquatic successional responses produced by continuous source nutrient enrichment.

WASTEWATER NUTRIENT LOADS

The wastewater loading trend, with accompanying Washington D. C. area population growth and municipal wastewater discharges into the estuary from 1913 to 1979 is presented in Table 3.

Comparison of river low flow and wastewater flow into the estuary finds that at low river flow, the sewage treatment plants contribute significant freshwater flow into the estuary (See Table 4). The percentages calculated here are only valid for low flow-draught conditions when storm runoff would not be present and be considered as a source. Percentages calculated in Table 3 during high flow (over Little Falls) are erroneous by being too high because storm flow occurred into the estuary, but was not used in the calculation. It is interesting to note that during the lowest flow recorded to date (1966), that wastewater discharges contributed 46 percent of the freshwater flow, and that for the data available the range was 6 to 22 percent with an average of approximately 12 percent, not correcting for storm runoff, which might lower the 6 percent to 3 percent.

The nutrient budget that existed in the Potomac in the mid- and late 60's is substantially different from the one that was present in the late 70's. The relative contributions and mass loadings from the Potomac River (measured at Chain Bridge) and from wastewater loadings have changed significantly, particularly for phosphorus.

A comparison is given in Chart 5 of Chain Bridge wastewater loads (MT/day) for 1968 and loads in the

Chart 5

Year	Chain Bridge			Wastewater Loads		
	Phosphorus MT/day	Nitrogen MT/day	N:P (by atoms)	Phosphorus MT/day	Nitrogen MT/day	N:P (by atoms)
1968	0.7	1.5	1.105	9.2	25.0	3.409
1978	0.5	1.4	0.874	2.6	22.4	19.76

Source: EPA (1969), Clark et al. (1980), and STORET

Table 4. Comparison of mean river low flow (over Little Falls into the estuary, with water supply diversions removed) to total Washington, D.C. wastewater flows in (m^3/s) with percentage of wastewater flow to total flow calculated.

Year	Mean* River low flow (July, Aug. Sept.) (m^3/s)	Total** Washington, DC wastewater annual flows (m^3/s)	Percent wastewater to river flow
1932	58.6	3.9	6
1944	62.0	7.3	10
1954	70.5	8.5	11
1957	53.1	9.2	15
1960	117.2	9.7	8
1964	53.0	11.9	18
1965	46.0	12.5	21
1966 (75 days) (July-Sept 13)	15.1	13.1	46
1967	150.4	13.5	8
1968	76.3	14.0	16
1969	153.2	14.0	8
1970	144.7	14.1	9
1977	56.8	15.8	22
1978	230.8	17.7	7
1979	318.8	18.8	6
1980	106.4	20.7	16

* USGS Towson, MD

** Summed from 8 treatment plants data reports river (above the estuary) at a similar flow by regression (2,800 cfs, 79.3 m^3/s) for 1978 which indicates that wastewater phosphorus loads have decreased by approximately 70 percent, while freshwater phosphorus inputs from the river to the estuary have decreased by approximately 30 percent in the upper estuary.

Under conditions that existed in the upper reach in the late 1970's, at flows above 5,000 ft^3/s (14.6 m^3/s), the freshwater input is the major contributor of nutrients to the upper reach of the Potomac; at flows between 2,000 to 5,000 ft^3/s, the wastewater discharges in the upper reach dominate the system, and at flows below 2,000 ft^3/s (56.6 m^3/s) during high temperature periods, biochemical processes dominate the upper reach.

DIFFUSE NUTRIENT SOURCES

Nutrient data or estimates on diffuse sources for the Potomac Estuary are generally unavailable or are rough estimates. However, based on scarce data, a mass loading can be estimated from nonpoint sources, point sources and benthic sediment releases. Tables 5 and 6 represent estimates for these sources for 1977 and 1978. The data in Table 5 is for a 53-day period (July 18 to September 7) during the summer of 1977. The data in Table 6 is for a 73-day period (July 17 to September 27) during the summer of 1978. In comparing the data of these two years, the varying hydrological conditions which existed in those two years must be taken into consideration. Nineteen seventy-seven was a low-flow year having an average summer flow of approximately 1,500 ft^3/s (42.5 m^3/s) and many localized storms of short duration, whereas the summer of 1978 was characterized by higher and more erratic flows that greatly influenced water quality (Clark et al. 1980). River flows during the 1978 study period ranged from 35,000 ft^3/s (991.2 m^3/s) to 2,200 ft^3/s (62.3 m^3/s), with an average flow of 6,900 ft^3/s (195.4 m^3/s). Rainfall during the two study periods was comparable with 6.4 inches (16.2 cm) in 1977 and 7.4 inches (18.8 cm) in 1978. In 1978, the basin-wide storms had greater impact on base flow and therefore increased the Chain Bridge (upper boundary of the estuary) input to the estuary. Although in some cases the loading of materials coming into the system are on the same order of magnitude, the storm-related inputs are delivered into the estuary on a very short time scale. These short pulses delivering large loadings may impose a shock on the system. Furthermore, if these loadings occur at a time of substantially reduced residence time, then nutrient expression (algal uptake) may be reduced. The significance of Tables 5 and 6 is that; (1) the CSO sources are insignificant as a source of macronutrients, (2) at low flow (1977 - 42.5 m^3/s), point sources are the dominant source of phosphorus, while at lighter flows (1978 - 195.4 m^3/s), the upper basin and the STPs contribute equal amounts of phosphorus, and (3) the contribution of phosphorus from the bottom is insignificant in the upper reach; but is the dominant source in the lower reach. These estimates need additional verification; they are presented here as a focus for future studies.

NITROGEN/PHOSPHORUS RATIOS

Using the concept of the nitrogen-to-phosphorus ratio as developed by Redfield, insight can be gained into the possible nutrients that limit the growth of phytoplankton in the

Table 5. Estimation of major nutrient loads (in million metric tons) for the upper Potomac River Estuary (1977 study period).

		Input Category (million tonnes)					
Parameter	Point Source (STP)*	Upper Basin*	CSO*	Urban	Benthic Release		
BOD_5	1.77	0.50	0.15	1.32			
Total N	1.22	0.14	0.01	0.14	Reach	I	0.24 (c)
						II	0.84 (c)
						III	4.54 (c)
Total P(d)	0.18	0.01	0.007	0.04	Reach	I	0.009 (c)
						II	0.14 (c)
						III	1.00 (c)

(a) combined sewer overflow

(b) storm runoff

(c) from USGS**:

	Reach	Station Locations
	I Tidal River	Rm 60-95
	II Transition Zone	Rm 38-60
	III Estuary	Rm 5-38

Total N (converted) from NH_4^+ flux; Total P from PO_4^{3-} as P

(d) as P

Days in Study Period: 53

Sources: *data from: Clark and Roesh, 1978; Champ, 1978, 1979.
**USGS, Callender, 1979, (Unpublished manuscript).

Table 6. Estimation of major nutrient loads (in million metric tons) for the upper Potomac River Estuary (1978 study period).

	Input Category				
Parameter	Point Source (STP)*	Upper Basin*	CSO*(a)	Urban*(b)	Benthic Release
BOD_5	2.99	3.22	0.21	1.90	
Total N	1.81	1.13	0.022	0.18	Reach I 0.33 (c)
					II 1.18 (c)
Total P(d)	0.18	0.18	0.009	0.07	Reach I 0.009 (d)
					II 0.20 (d)
					III 1.41 (d)

(a) combined sewer overflow

(b) storm runoff

(c) from USGS:

Reach		Station Locations
I	Tidal River	Rm 60-95
II	Transition Zone	Rm 38-60
III	Estuary	Rm 5-38

Total N (converted) from NH_4^+ = flux; Total P from PO_4^{3-} as P

(d) as P

Days in Study Periods: 73

Sources : * data from: Clark et al., 1980 Champ, 1978, 1979.
** USGS - (Callender, 1979, unpublished manuscript).

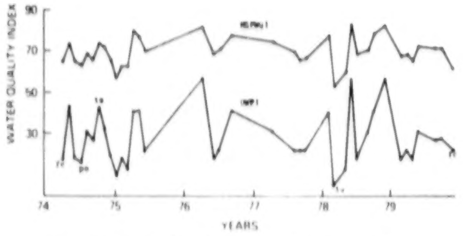
estuary. The "Redfield Numbers" are based upon the concept that phytoplankton are composed of approximately 106 carbon atoms for every 16 nitrogen atoms and every 1 phosphorus atom. Algae, therefore, need these three elements in roughly that proportion. While individual algal species may have differences in the C:N:P stoiciometry, in general marine algae have the same relative ratios. Therefore, an N:P ratio of greater than 16 has a tendency to reflect a situation in which phosphorus is the limiting nutrient. Under these conditions, the available orthophosphate concentrations will be on the order of a few $\mu g/l$ during the peak algal biomass production. If nitrogen is limiting, the N:P ratio will generally be less than 16. The sum of the concentrations of nitrites, nitrates, and ammonia will be on the order of 20 to 30 $\mu g/l$ during the bloom. Table 7 presents N:P ratios both as total and as inorganic for 1969 to 1979. The effect of phosphate removal at Blue Plains is easily seen in the shift in wastewater ratios from 1969-1970 to 1977-1979, with the change in ratios indicating a shift toward being phosphorus limited. The calculation of these ratios yields great insight into the nutrient processes in the setuary. For instance, phosphorus was never shown to be limiting in the late 1960's; however, the system appears to be shifting toward a phosphorous limiting state in Reach 1 in 1979. It should be noted that there is a downstream trend of increased release of phosphorus and nitrogen from bottom sediments.

WATER QUALITY TRENDS

To complement the previous wastewater nutrient loading trends and nutrient levels and trends in the estuary, we include here data from papers by Noland and Champ (1979), Noland (1980) and Noland and Champ (in manuscript). One of the disadvantages in interpreting water quality parameters is the tendency to construe parameter data individually, which leads to oversimplification and neglects consideration of the body of water as an interrelated system. Consequently, several water quality indices (WQI) have been developed which combine the values of many highly variable (both temporally and spacially) parameters into a single value (or index) representing general water quality. These WQI provide standardized mathematical methods of aggregating water quality data into values that permit an objective assessment of the system. Noland and Champ utilized both the National Santitation Foundation Water Quality Index-Modified (NSFWQI-M), which uses a weighted product aggregation function, and the Ott Water Pollution Index (OWPI), which is based on the minimum operator concept, in order to conduct water quality trend analyses at selected stations. These indices combine the following water quality parameters: dissolved oxygen, fecal coliforms, pH, nitrates, phosphates, temperature, BOD_5, total solids, and turbidity. Figures 3 and 4 plot index values for each station for indicated years. Figure 3 groups five stations that cover the main stem of the Potomac River, and Figure 4 groups three stations in Reach I of the estuary--two stations above Blue Plains and one below. The ratio of the variation in each water quality index attributable to regression against time along with all other variation in the WQI (F value), was used to derive the probability that a trend at any given station was statistically significant. The points on the graphs were connected only for clarity, and not to imply representation of water quality between monitoring times. If a high probability

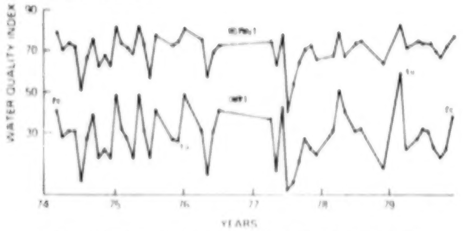
MAIN STEM POTOMAC RIVER

MD. RT. 51
RM – 277
PAW PAW, W.VA.



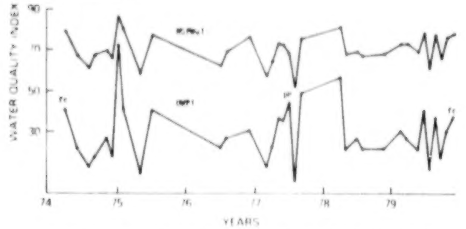
WATER QUALITY AT POT 2766, IN THE POTOMAC RIVER MAIN STEM AT PAW PAW, W.Va. NO SIGNIFICANT TREND WAS DISCERNIBLE FROM THE DATA

BELOW MD. RT. 34
RM – 183
SHEPHERDSTOWN, MD



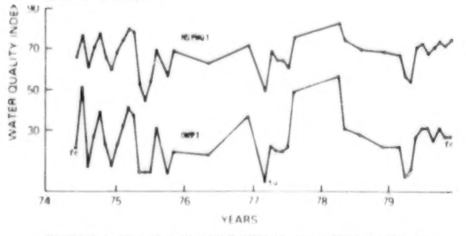
WATER QUALITY AT POT 1830, THE POTOMAC RIVER AT SHEPHERDSTOWN, MD. NO SIGNIFICANT TREND WAS DISCERNIBLE FROM THE DATA

U.S. RT. 15 BRIDGE
RM – 160
PT. OF ROCKS, MD



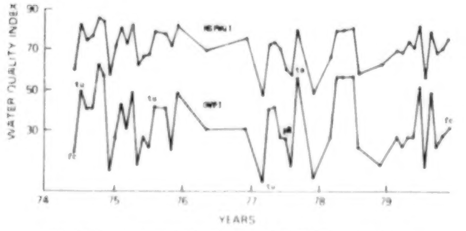
WATER QUALITY AT POT 1595, THE POTOMAC RIVER AT POINT OF ROCKS, MD. NO SIGNIFICANT TREND WAS DISCERNIBLE FROM THE DATA

MD. RT. 107
RM – 147
WHITE'S FERRY, MD



WATER QUALITY AT POT 1471, THE POTOMAC RIVER AT WHITE'S FERRY, MD. NO SIGNIFICANT TREND WAS DISCERNIBLE FROM THE DATA

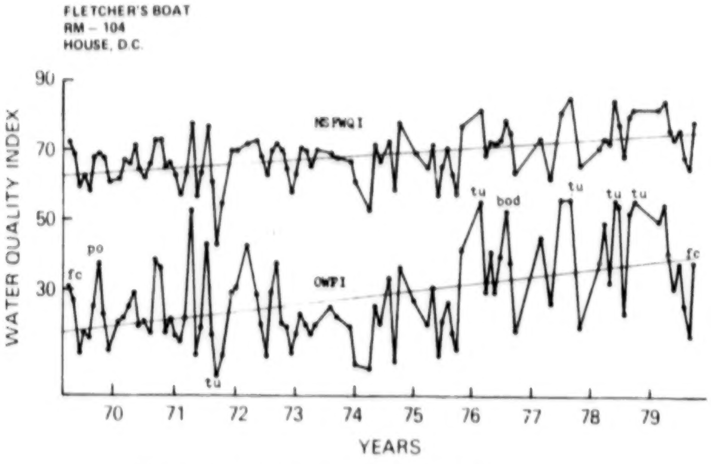
LITTLE FALLS DAM
RM – 118
BETHESDA, MD



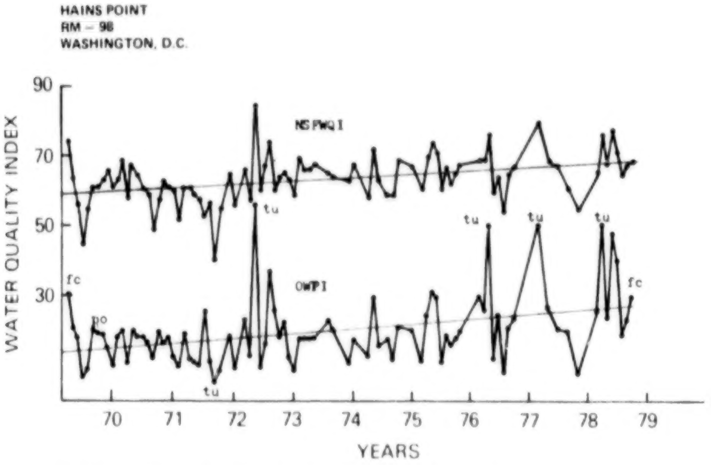
WATER QUALITY AT POT 1184, THE POTOMAC RIVER ABOVE LITTLE FALLS, MD. NO SIGNIFICANT TREND WAS DISCERNIBLE FROM THE DATA

Figure 3. Plots of the NSFWQI-M and OWPI Indexes for five stations on the Main Stem, Potomac River.

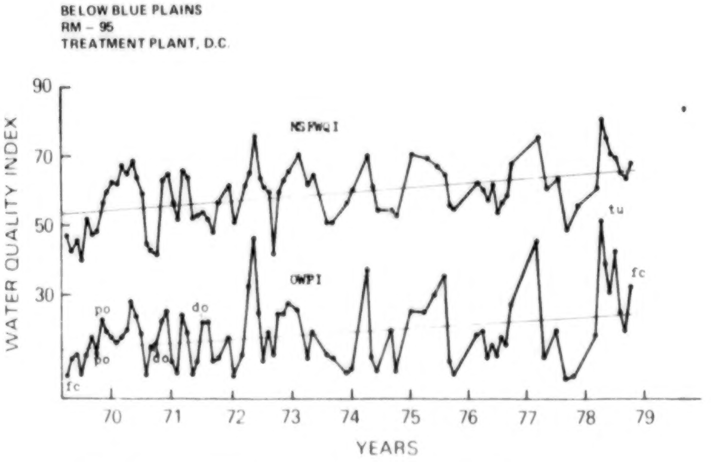
POTOMAC RIVER ESTUARY


FLETCHER'S BOAT
RM – 104
HOUSE, D.C.

WATER QUALITY AT 101001, AT FLETCHER'S BOAT HOUSE IN D.C.
A SIGNIFICANT INCREASING TREND WAS INDICATED BY BOTH WQI.


HAINS POINT
RM – 98
WASHINGTON, D.C.

WATER QULAITY AT 101007, AT HAINS POINT IN D.C.. A SIGNIFICANT INCREASING TREND WAS INDICATED BY BOTH WQI.


BELOW BLUE PLAINS
RM – 95
TREATMENT PLANT, D.C.

WATER QUALITY AT 101011, BELOW THE BLUE PLAINS SEWAGE TREATMENT PLANT IN THE POTOMAC ESTUARY. A SIGNIFICANT INCREASING TREND WAS INDICATED BY BOTH WQI.

Figure 4. Plots of the NSFWQI-M and OWPI Indexes for three stations in Reach I of the Potomac River Estuary.

Table 7. Nitrogen/phosphorus ratios (by atoms).

Source/Zone	1969		1970		1977		1978		1979	
	TN/TP	In N/ In P	TN/TP	In N/ In P	TN/TP	In N/ In P	TN/TP	In N/ In P	TN/TP	In N/ In P
Upper Basin										
Yearly	24	35	29	45	24	44	31	48	32	49
Four-month	23	36	23	35	22	39	25	37	27	43
Wastewater	5	6	6	7	15	18	22	33	32	34
Reach I	15	13	13	10	16	18	25	60	38	80
Reach II	14	11	5	9	5	12	12	25	29	
Reach III	6	3	5	2					9	10

Sources: Water quality data sheets, EPA Central Regional Laboratory, and EPA STORET.
In = Inorganc

(around 90 percent or greater) of a trend was indicated at a station, the regression line of best fit was plotted on the graph.

There was good agreement between the two indices. Increased values (or slope) is an improvement in water quality. In comparing Figures 3 and 4 it is interesting to note that the trend analysis overcomes the low-flow and high-flow years. For instance, the index is low on the main stem for 1977 and high for 1978 at Point of Rocks and White's Ferry. The effect is reversed in the estuary for the same years, turbidity being the dominant parameter for OWPI. The significance of these two figures is that the water quality trend in the upper reach of the estuary showed significant improvement whereas the main stem stations did not, and both were subjected to the same variations in flow. However, Reach I was subjected to wastewater loadings which had extensive phosphate removal (over 80 percent) and were phosphate reduced with subsequent reduction in algal productivity (biomass, chlorophylls, BOD,). All of this was expressed as improved water quality in the trend analysis, even though the system was overloaded with nitrogen. The benefit to the system to utilize the excess nitrogen at a slower rate, therefore maximizing the temporal and spatial factors for wastewater dispersion and dilution to background levels further down the estuary.

SUMMARY

Hypotheses which can be drawn from these studies are (1) phosphorus removal in the wastewater is a significant factor in the improvement in water quality in the upper half of the estuary. Also, it should be noted that the water quality downstream may be impaired in the long term by the depressed-delayed nutrient expression; however, the lower reaches appear to currently assimilate the downstream levels; (2) phosphorus reduces algal growth in the upper estuary in Reach I and to a lesser extent in Reach II; (3) nitrogen levels may regulate algal growth in Reach III, and (4) in Reach II light penetration (quantitative and qualitative) may regulate algal growth. We expect to pursue this last hypothesis in a subsequent publication (see research proposed in Champ et al. 1980).

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CHAPTER 14

BASIN MANAGEMENT AND FRESHWATER INFLOW

CHARACTERIZATION OF FRESHWATER INFLOW MODIFICATION TO ESTUARIES RESULTING FROM RIVER BASIN DEVELOPMENT

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ABSTRACT

Three approaches for determining quantity and modification of freshwater inflow to estuaries are presented: Continental-scale assessment, statistical studies of long-term records at the mouth of a river, and river basin modeling. The statistical approach is illustrated using long-term streamflow records for the Brazos River, Texas and the Santee River, South Carolina. River basin modeling, illustrated using data from the lower Santee River Basin, is believed to be the best approach for general field studies.

INTRODUCTION

A network of long-term coastal gauging stations, operated by the U.S. Geological Survey and other agencies, is available for characterizing streamflow quantity and variation into U.S. estuaries. In recent years, sediment and water quality data have also become available at selected sites. To address an objective of determining the magnitude and modification of quantity, quality, and timing of freshwater inflows to estuarine areas, three hydrologic approaches are presented: continental scale assessments, statistical studies of long-term gauged records near river's mouth, and river basin modeling. Each approach represents a different degree of focus and detail.

CONTINENTAL SCALE ASSESSMENT

According to Iseri and Langbein (1974), the outflow of all streams from the conterminous United States into the oceans or across its boundaries is about 2 million cubic feet per second. Of this total, more than 75 percent is accounted for by eleven independent streams (Mississippi, Columbia, Yukon, Atchafalaya, Mobile, Susquehanna, Sacramento, Apalachicola, Colorado, Hudson, and Delaware Rivers). The remaining 25 percent is discharged through a host of comparatively minor coastal streams. Such results are the product of careful assessments performed by U.S. Geological Survey hydrologists during the 1960's as part of the U.S. contribution to the International Hydrological Decade. Completed studies of freshwater inflow from the conterminous United States (Wilson and Iseri 1967) are examples of these assessments. While useful for a variety of purposes, the assessments are of limited use in determining modifications of freshwater inflows.

STATISTICAL STUDIES OF FLOW AT MOUTH OF RIVER

The general character of modifications of freshwater flow to particular estuaries can be approximately deduced by a statistical study of a long-term gauging record if available near the mouth of a particular river. Such studies, by introducing time variation, have more focus and detail than continental assessments for magnitude of flow volume alone. The assumption in such a hydrologic approach is that long historic time series have embedded within them the effects of modifications due to upstream river basin developments. Under proper circumstances, these effects or trends can be discriminated using nonparametric statistical trend methods such as rank correlation methods (Dixon and Massey 1957). However, because freshwater time series are natural statistical series with significant climatic and random variation, embedded man-made modifications must be fairly signifiant to allow detection of shifts and/or trends. This constraint introduces a definite limitation to the approach.

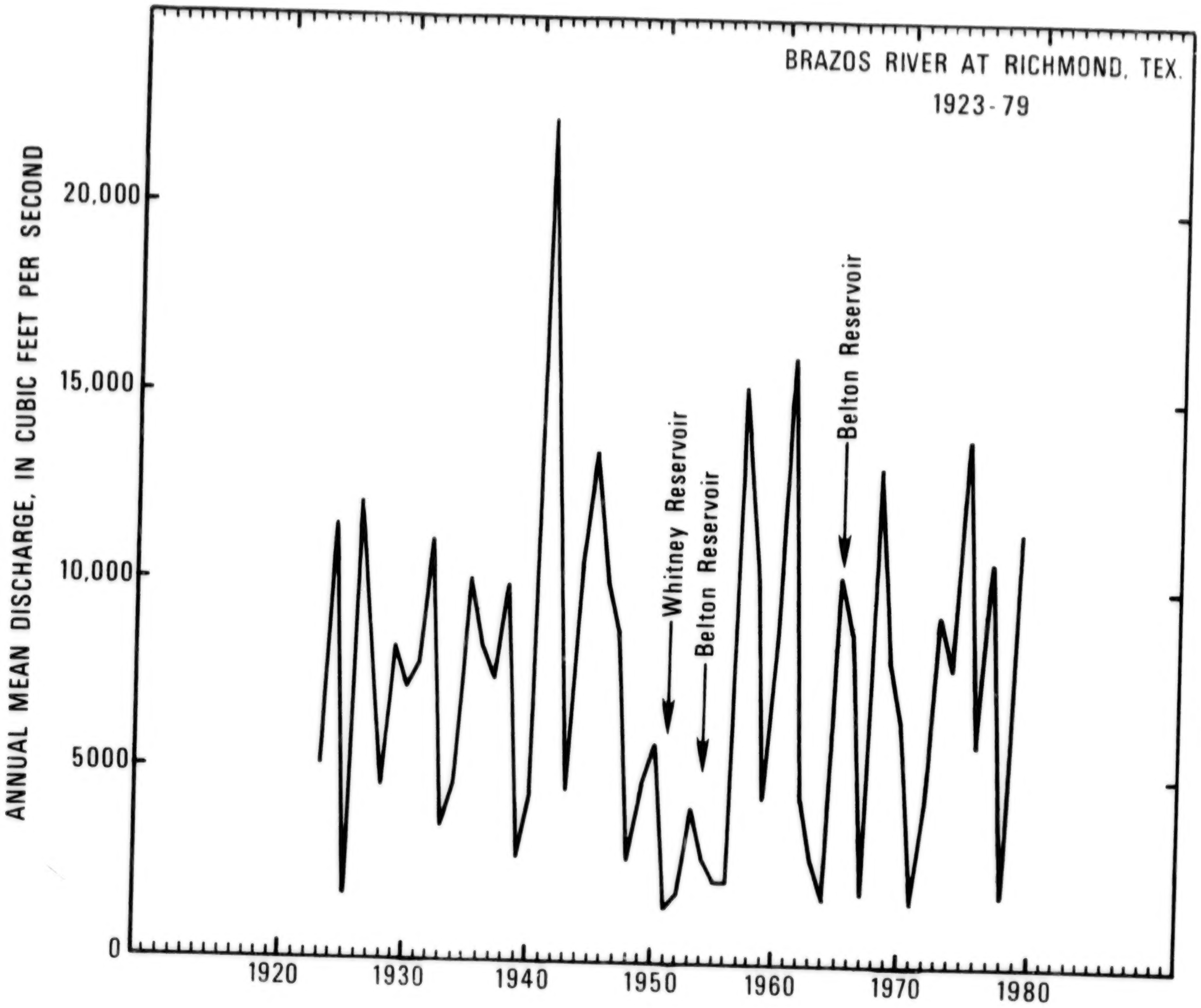
As an example, the gaged record of Brazos River at Richmond, Texas located at mile 93 and including 44,020 square miles, has experienced modifications due to upstream diversions, reservoir regulation and floodwater detention structures. Figure 1 is a plot of annual mean discharges gaged at Brazos River at Richmond, Texas for the period 1923-79. Note that three large reservoirs--Whitney Reservoir in 1951, Belton Reservoir in 1954, Waco Reservoir in 1965--have been constructed during the period of gauged record. Note also that the record is dominated by the fairly regular cyclical climatic pattern that seems to pervade the 48 conterminous states. Figure 2 is a plot of the 9-year moving averages of annual streamflows for Brazos River at Richmond, Texas as compared to an average 9-year pattern for the plains region as compiled by Langbein and Slack (1980). The dominance of long-term regional climatic effects in the flow pattern is clear. Thus, effects due to river basin modification are expected to be relatively undiscernable by statistical trend techniques. Figure 3 is a plot of annual mean discharges for Santee River at Ferguson, South Carolina for 1909-78. The Santee River, including 14,600 square miles, has experienced a drastic change in flow regime caused by complete regulation and rediversion. In this case, statistical trend methods can easily discriminate the effects of river basin modification which are clearly dominant to climatic effects.

In general, statistical extraction of trends in long-term river records due to basin modifications may be a tenuous exercise. Also, while useful and enlightening as to the effects of past changes, statistical trend studies of historic records offer little opportunity for assessment of future alternative watershed modification and associated impacts on estuarine areas.

RIVER-BASIN MODELING

A third approach for determination of freshwater inflow modification to estuaries is deterministic modeling of river basin hydrology. This approach overcomes most of the liabilities of the first two approaches provided adequate physical and hydrologic data exist for model calibration and verification.

Deterministic models use hydrologic and hydraulic tools such as watershed modeling, hydraulic flow routing through channels and structures, and transport modeling of sediment and water quality. Currently under development by the Survey is the Large River Basin Transport Model (LRBTM). LRBTM routes daily flows and loads using a network of existing stream gauging and rainfall stations as a data base for calibration and verification. Long-term


BRAZOS RIVER AT RICHMOND, TEX.
1923-79
ANNUAL MEAN DISCHARGE, IN CUBIC FEET PER SECOND
20,000
15,000
10,000
5000
0
1920
1930
1940
1950
1960
1970
1980
Whitney Reservoir
Belton Reservoir
Belton Reservoir

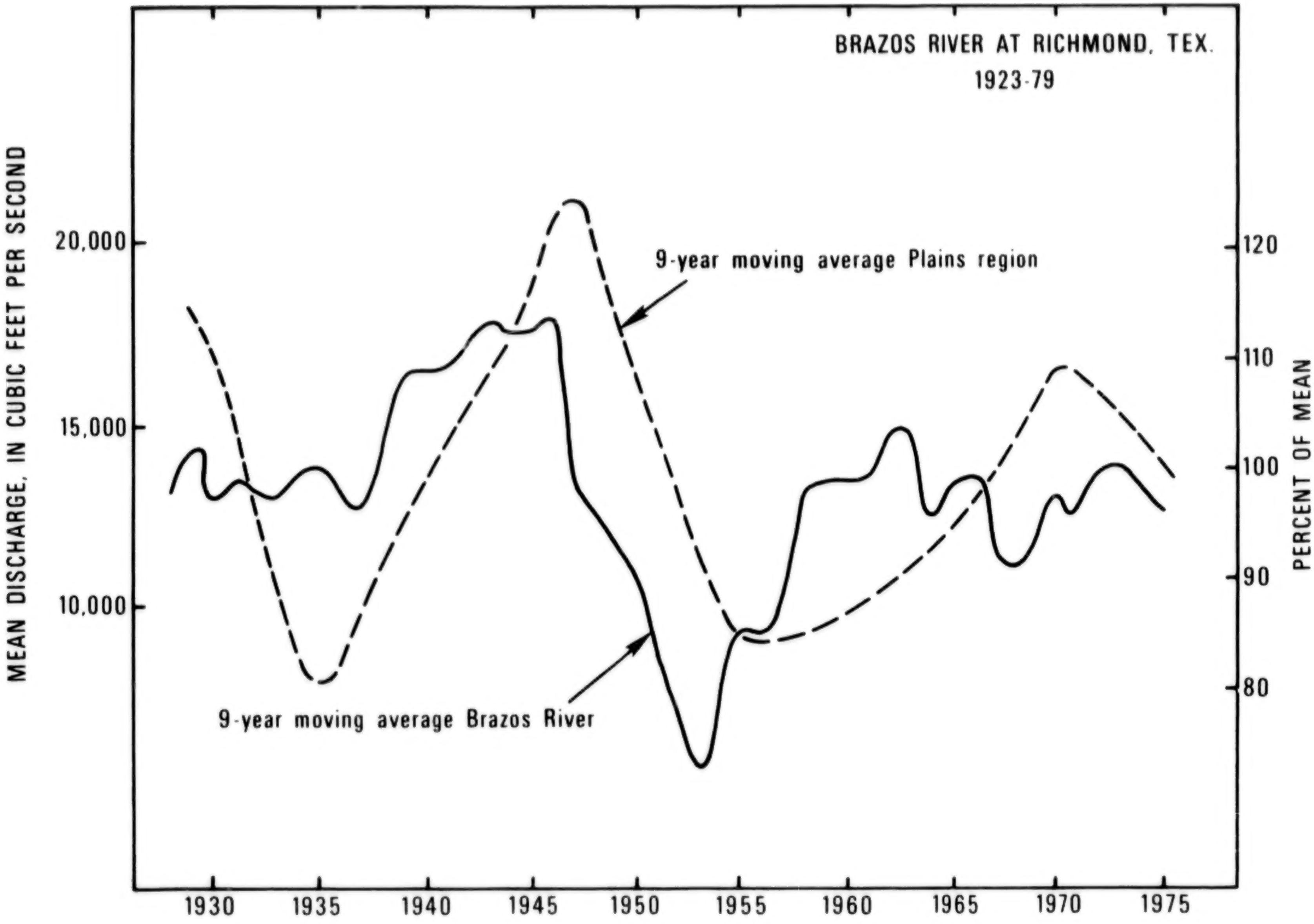


Figure 2. Nine-year moving averages of Brazos River, Richmond Texas, 1923-79.

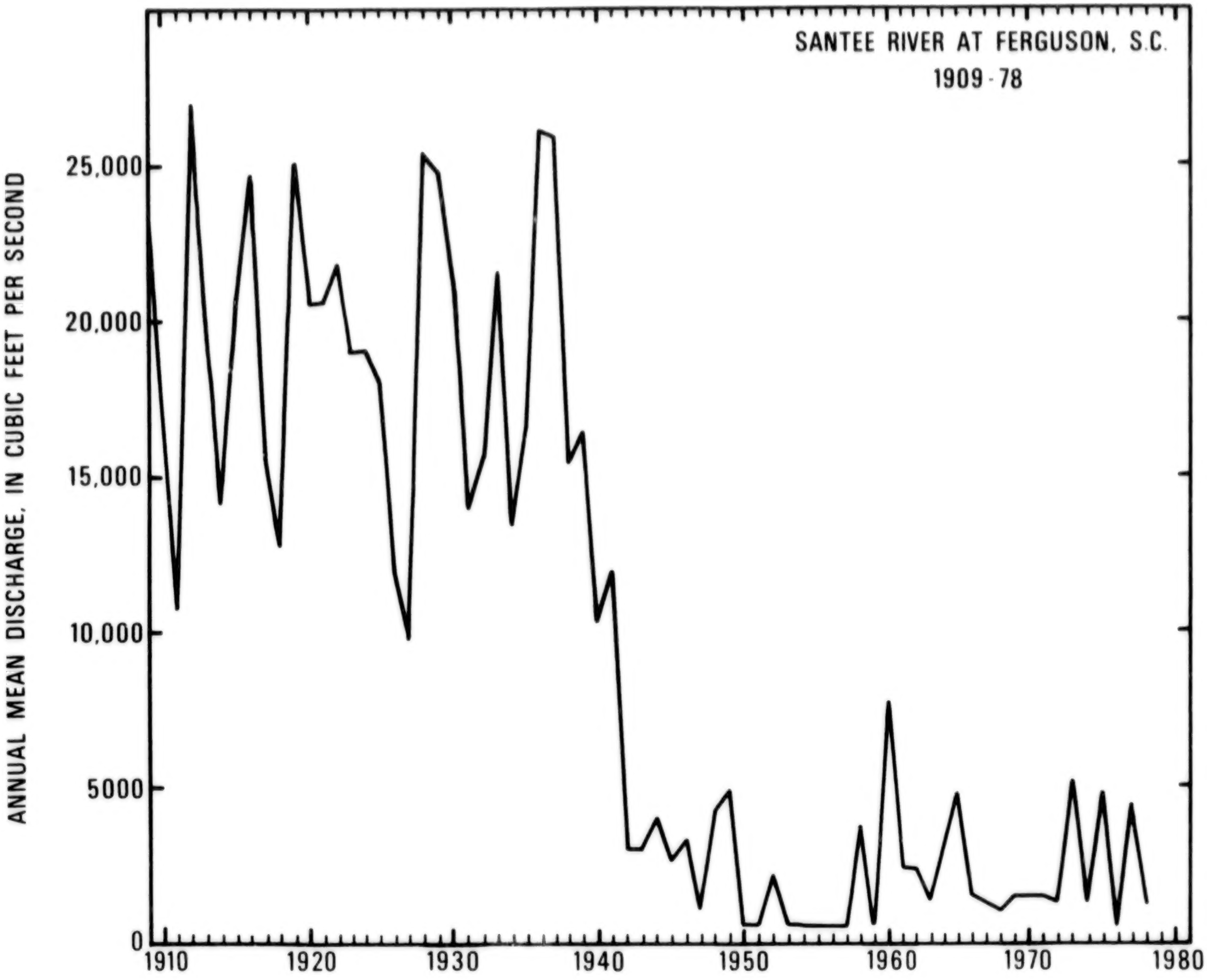


Figure 3. Discharge of Santee River, Ferguson, S.C., 1909-78.

(20 to 50 year) simulations are possible depending on available data. Completed studies include river basin modeling of the upper Kentucky River Basin (Shearman and Swisshelm 1973); the Susquehanna River Basin (Armbruster 1977); the Flambeau River, Wisconsin (Krug 1976); and the Santee River Basin, South Carolina (Jeffcoat et al. 1976).

Figure 4 shows a map of the lower Santee River Basin. River flows are dominated by the operation of the Lakes Marion-Moultrie reservoir system. Streamflows, except for a small fish-hatchery flow and large flood flows, are diverted out of the basin through Lake Moultrie for hydropower production. The purpose of the use of LRBTM in the case of the Santee River basin study was to optimize power production through a study of reservoir operating rules. However, the model is fairly general and could be used to simulate various water resource scenarios. The model, which incorporates an inflow component, a diversion-canal component, and a reservoir system component, is capable of evaluating the performance of the reservoir system for a variety of operating rule conditions. All model components were verified using observed reservoir input and output data for a 6-year (1967-72). In addition, a long-term 31-year simulation under present and alternate rules of operation `was performed and the results summarized statistically. Figure 5 shows a comparison of observed and computed flows for Santee River at Fort Motte, South Carolina for March 4 - April 18, 1973; figure 6 shows a comparison of mean monthly actual and computed values of discharge used for power production at Lake Moultrie (1967-72). Similar comparisons were obtained for Santee River near Pineville (which represents flood spills from Lake Marion) and for mean monthly discharge in the Lakes Marion-Moultrie Diversion Canal.

CONCLUSIONS

The use of river-basin modeling is suggested as the best approach for determining the modification of quantity, quality, and timing of freshwater inflows to estuarine areas. The LRBTM model under development by U.S. Geological Survey will now model river flows and has been tested in a number of field studies. LRBTM is currently being modified to model sediment and water quality parameters.

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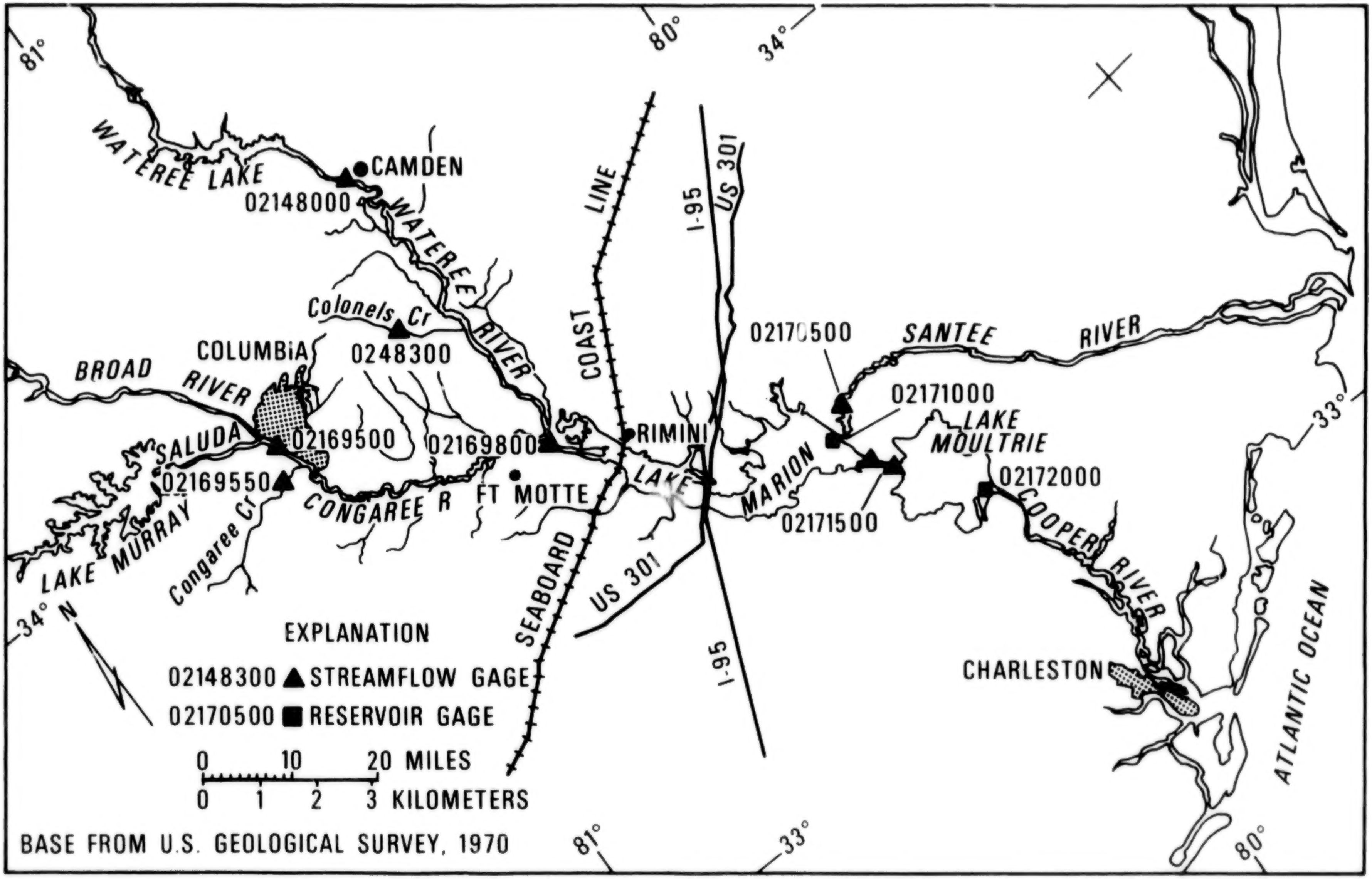

Figure 4. Lower Santee River Basin, S.C.

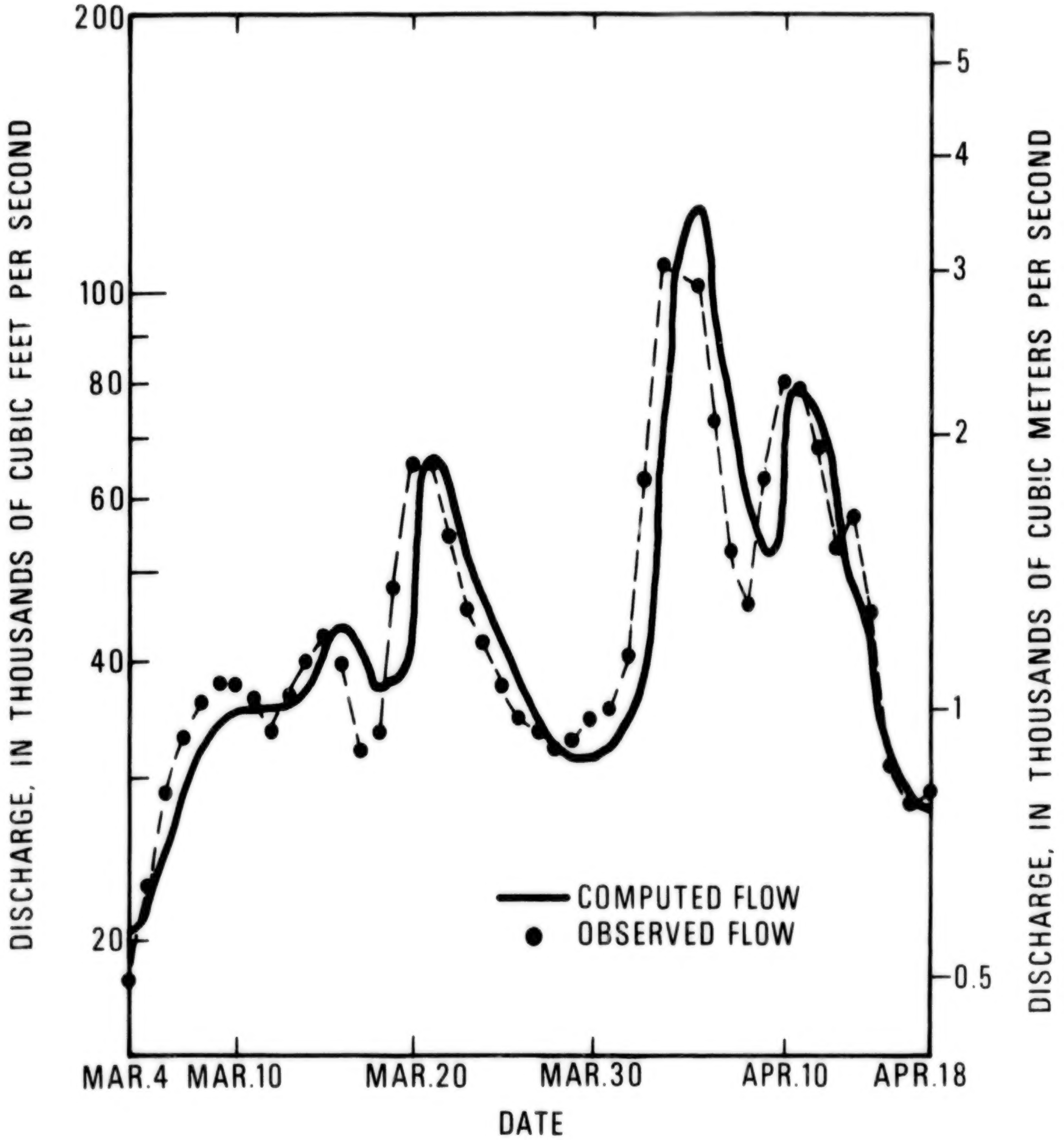

Figure 5. Observed and computed flows of Santee River , Fort Motte, South Carolina, from March 4 to April 18, 1973.

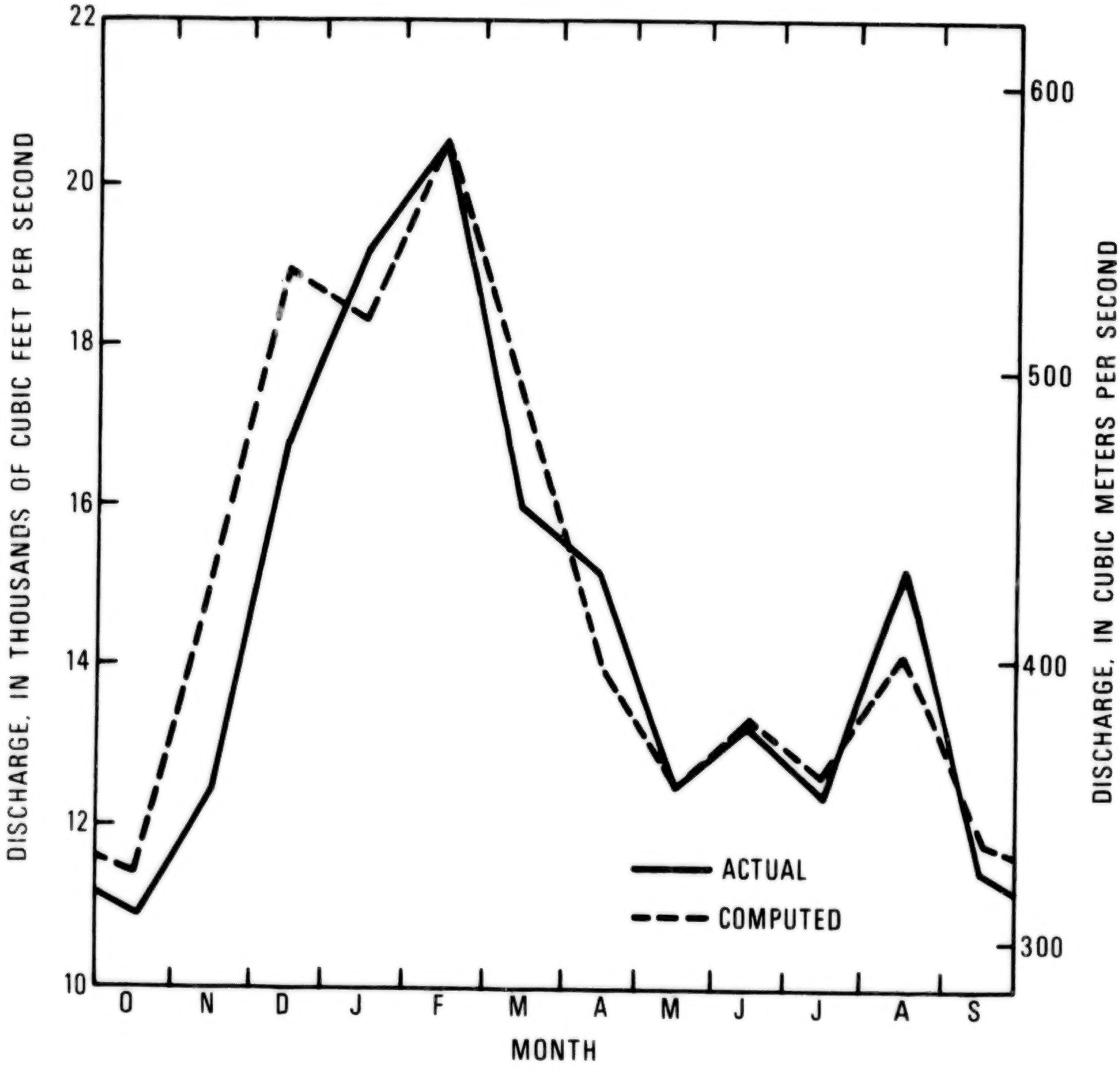

Figure 6. Computed and actual discharges used for power production at Lake Moultrie, South Carolina, (1967-72).

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FRESHWATER FLOW RATES AND DISTRIBUTION WITHIN THE EVERGLADES MARSH

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ABSTRACT

Situated in Everglades National Park is the Shark River Slough, a major drainageway conveying fresh waters from upstream impoundments to downstream estuaries. In 1970 a minimum annual flow rate of 260,000 acre-feet was mandated by the U.S. Congress to be delivered along the slough's northern boundary at 24 gravity control flood gates located at four structure sites. The intensively manipulative management of these headwater flow rates requires inflow and downstream hydrologic monitoring within a wetland system which is different from the more classical riverine/estuarine systems. Slough water depths range from 0 to 3 feet, slough widths vary from 9 to 17 miles and hydraulic gradients are 2 to 3 inches per mile producing extemely small velocity vectors characteristic of sheet flow hydraulic regimes. New techniques were developed to measure discharge rates and water distributions within the slough and intensive monitoring programs have been conducted at inflow control structures. Sheet flow rates, aerial distribution and volumetric storage were measured seasonally utilizing tracer dye field experiments and satellite imagery coupled with a staff gauge grid network. Small velocities, well below the levels of detection by conventional instrumentation from zero to 0.035 feet per second, were measured. When coupled with cross-sectional area calculations, a reasonable estimate of Shark River Slough contributions to the estuarine region was produced (flow rates of 200 to 2000 cubic feet per second). Freshwater distribution within the Shark River Slough was subject to seasonal inundation fluctuating between 90,000 and 245,000 acres providing storage estimates between 26,000 and 208,000 acre-feet for the dry and wet seasons respectively.

INTRODUCTION

The Shark River Slough is a very wide, shallow and sluggish stream flowing from the northern boundary of Everglades National Park to the bays and estuaries along the park's southwest coast. It contains 245,000 acres of marshland consisting primarily of emergent and floating vegetation interspersed with tree islands. Within the park, flow is uncontrolled, unlike the area north and east of the park boundary where a maze of canals, levees, pumping stations and gated control structures regulate marsh flow (Figure 1). Surface waters enter the park through the S-12 structures which allow water from Conservation Area 3 to flow beneath the Tamiami Trail and from the Northeast Shark Slough which is hydraulically part of the Shark Slough but lies outside the park's boundary. A minimum annual delivery of 260,000 acre-feet is supplied to Shark Slough through the S-12 structures which

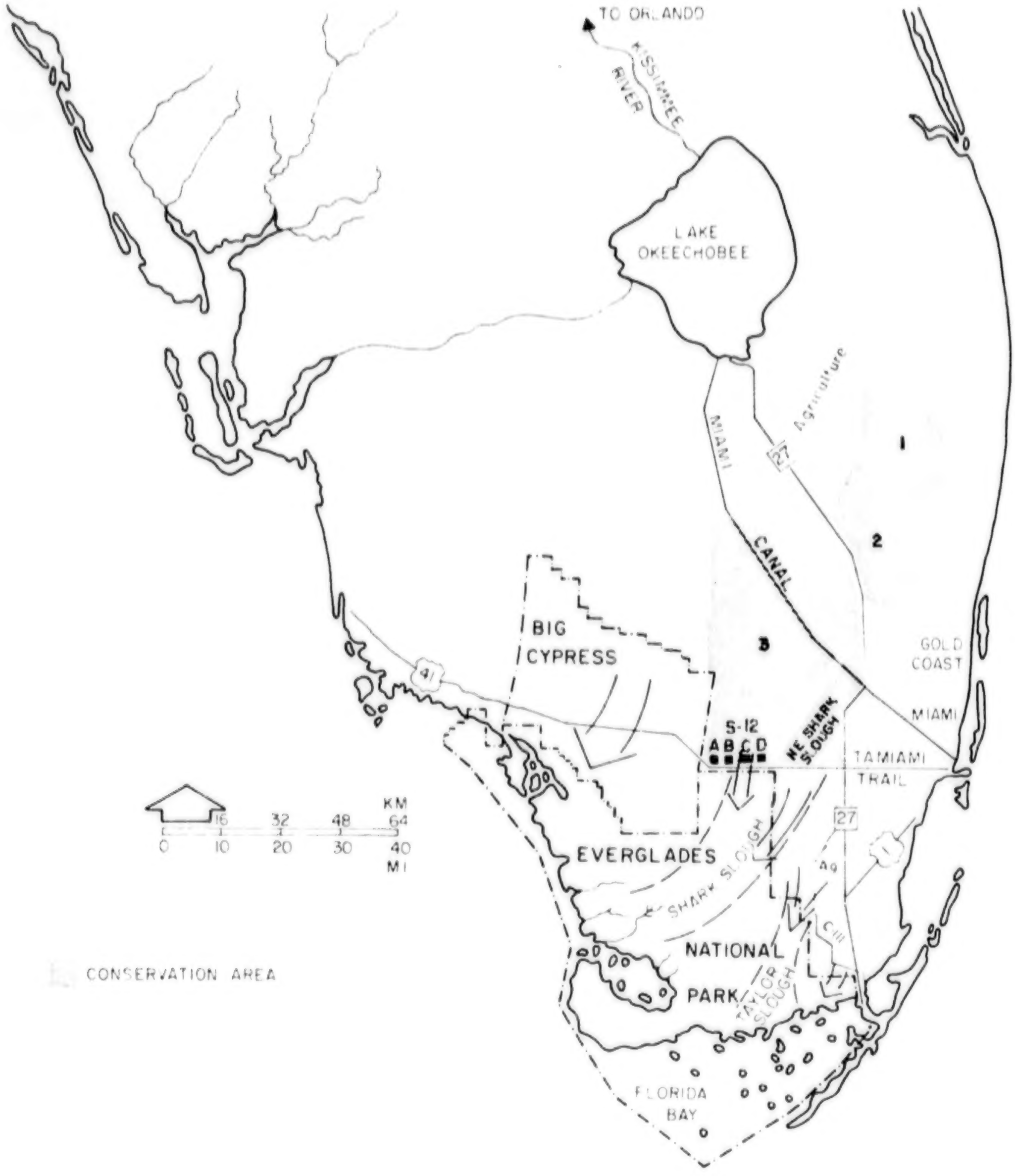


Figure 1. Surface Water Flows to Everglades National Park

represent the last site where conventional hydraulic measurements can be made.

An understanding of the flow characteristics and surface water distribution within the park required new techniques and approaches because classical hydraulic flow control sections employed in more conventional systems were absent. Presented herein are the results of determining velocities, flow rates, cross sectional areas, aerial distribution and volumetric storage for a marsh system which experiences seasonal water level fluctuations, variable slough boundaries extending in width as much as 9 to 17 miles, hydraulic gradients of only 2 to 3 inches per mile, channel depths of 0 to 3 feet, and velocities less than 0.035 feet per second. The knowledge gained through these investigations should help in managing upstream surface water deliveries to the park, provide the hydrologic component for wetland ecological studies, and assist in understanding freshwater contributions to downstream estuarine ecosystems.

DISCUSSION

SHEET-FLOW RATE DETERMINATION

Velocities encountered within Shark River Slough were small, being orders of magnitude less than those measurable by conventional Price- or Pygmy-type cup propeller velocity meters. Tracer techniques were thus employed using rhodaminewt dye which is ultimately detected due to its fluorescence. The set use of this dye for stream measurements was reported by Buchanan (1964), for estuarine and inshore waters by Pritchard and Carpenter (1960), and later specific details as to fluorometric procedures were published by the USGS (Wilson 1968). In addition to providing low velocity rate data, these tracer dye experiments also provided a method for calculating longitudinal dispersion coefficients. A description of this method will be published elsewhere and should prove useful in determining chemical and pollutant transport within the slough.

Dye studies were conducted along an east-west transect of Shark Slough in each of three hydrobiological zones namely: open marsh, intermediate vegetation and dense vegetation zones which constitute the inundated areas of the slough (Figure 2). These zones were selected based on their hydraulic properties where the greatest and least flow resistivities were anticipated in dense vegetation and open marsh zones respectively and determined by Landsat satellite multispectral data (Rose and Rosendahl 1979). Water samples were collected 20 feet down stream from the dye injection site every five minutes and their fluorescence was subsequently measured using a Turner Model II fluorometer powered by a portable electric generator. When the entire dye mass had passed the downstream monitoring site a concentration versus time curve could be constructed. During the period January 31, 1978 to January 24, 1979, twenty-seven such field experiments were conducted in each of three hydrobiological zones providing 81 dye concentration versus time curves. These experiments were conducted on a seasonal basis reflecting wet (rising-water levels, June through October), and dry (falling-water levels, November through May seasons. The stage hydrograph for the continuous water level recording station P-33 located within the center of Shark River Slough shows these historic water level fluctuations (Figure 3a). Velocities were subsequently calculated by noting the time of passage of the peak

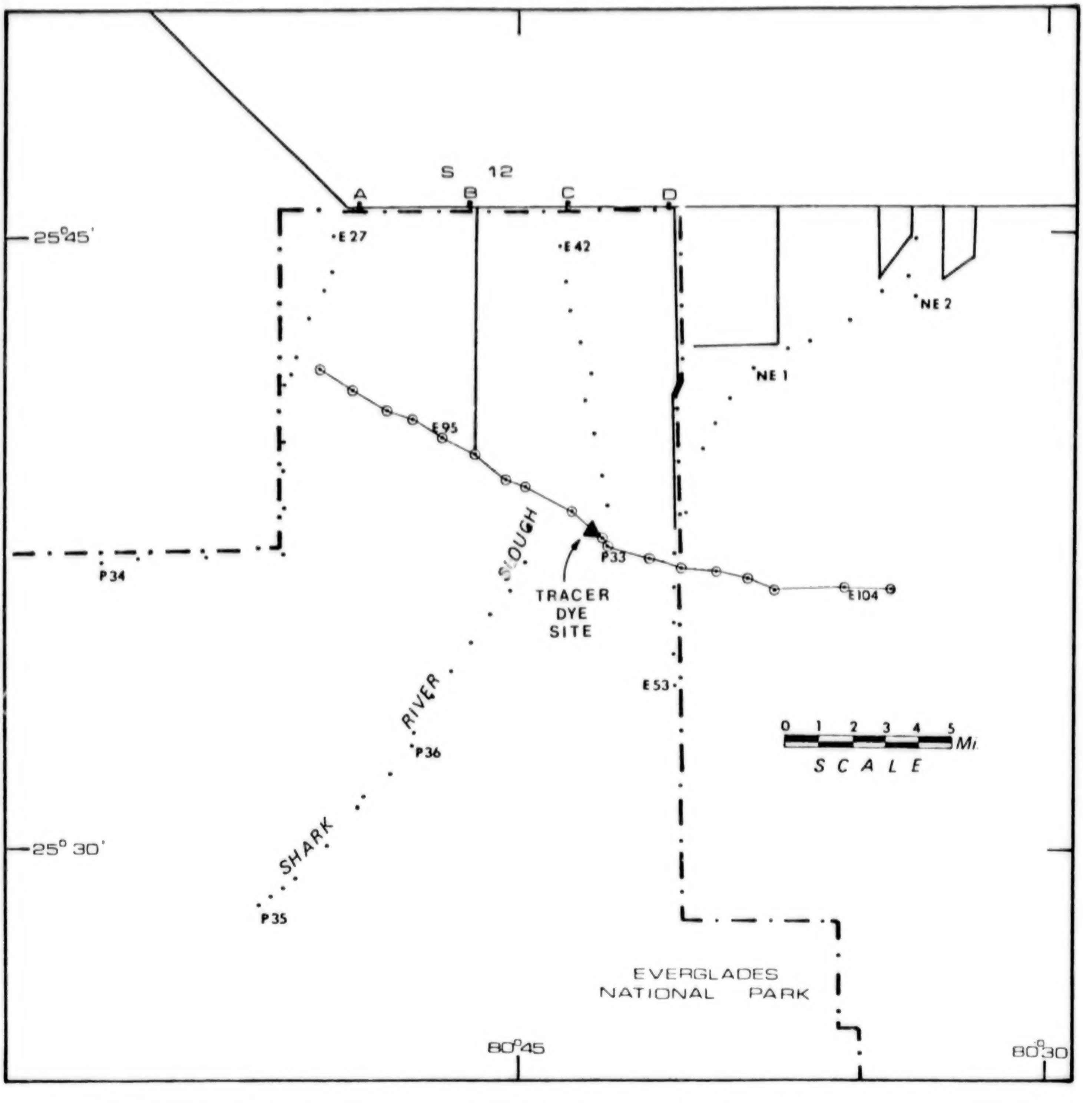


Figure 2. Shark Slough Transect and Gauging Sites

from the C versus T curve and using the downstream travel distance of 20 feet. Velocities were thus obtained by:

$$V = {}^{X}/_{t} \qquad (1)$$

where:

V = Average velocity of water mass

X = Travel distance = 20 feet

t = Time of passage of peak of C versus T curve.

Velocities in the open marsh varied from 0.005 to 0.034 feet per second for water depths of 1.0 to 2.1 feet, in intermediate vegetation from 0.003 to 0.023 feet per second for water depths of 0.3 to 1.4 feet and in the dense vegetation zone from 0 to 0.022 feet per second for water depths of to 1.2 feet. These data compare with the results of an earlier investigation by the U.S. Army Corps of Engineers (1954) for Conservation Area 2 located 35 miles north of Everglades National Park which found marsh velocities from 0.015 to 0.050 feet per second for water depths of 1.07 to 4.82 feet.

Velocity versus water depth relationships were developed for each zone as well as combinations thereof. Data from open marsh and intermediate vegetation zones were combined so that a single equation could be obtained relating velocities to depth regardless of the specific hydrobiological zone (Figure 3b). By statistically correlating all possible combinations of the three zones, it was found that these two zones could be related with a correlation coefficient of r = 0.7 compared to all zones combined of r = 0.5. An areal analysis of the slough using Landsat multispectral imagery found only 11 percent of the slough to be occupied by the dense vegetation zone and analysis along the seventeen-mile transect passing through the dye study site also found only 10 percent dense vegetation. The equation relating velocity to depth was determined to be:

$$\text{Velocity} = 0.012 \times \text{Depth} + 0.001 \qquad (2)$$

Equation (2) provides a means of calculating average velocities along a transect constructed across the slough utilizing measured water depth at 18 sites.

Flow rates were calculated along the transect by first obtaining both velocity and cross-sectional area perpendicular to the direction of flow at each of 18 flow sections which together comprise the total flow cross-sectional area. That is:

$$Q = VA \qquad (3)$$

or

$$Q = \mathop{}\limits_{i=1}^{n} V_i A_i \qquad (4)$$

where

$n = 18$

$V_i = 0.012D_i + 0.001$

or

$$Q = \mathop{}\limits_{i=1}^{18} A_i \, (0.012\, D_i + 0.001) \qquad (5)$$

where A_i = Area = $W_i \, D_i$

D_i = Depth

W_i = Width

Q = Total Discharge

V_i = Velocity

Water depths were measured biweekly along the transect at 18 sites from January 12, 1978 to July 12,

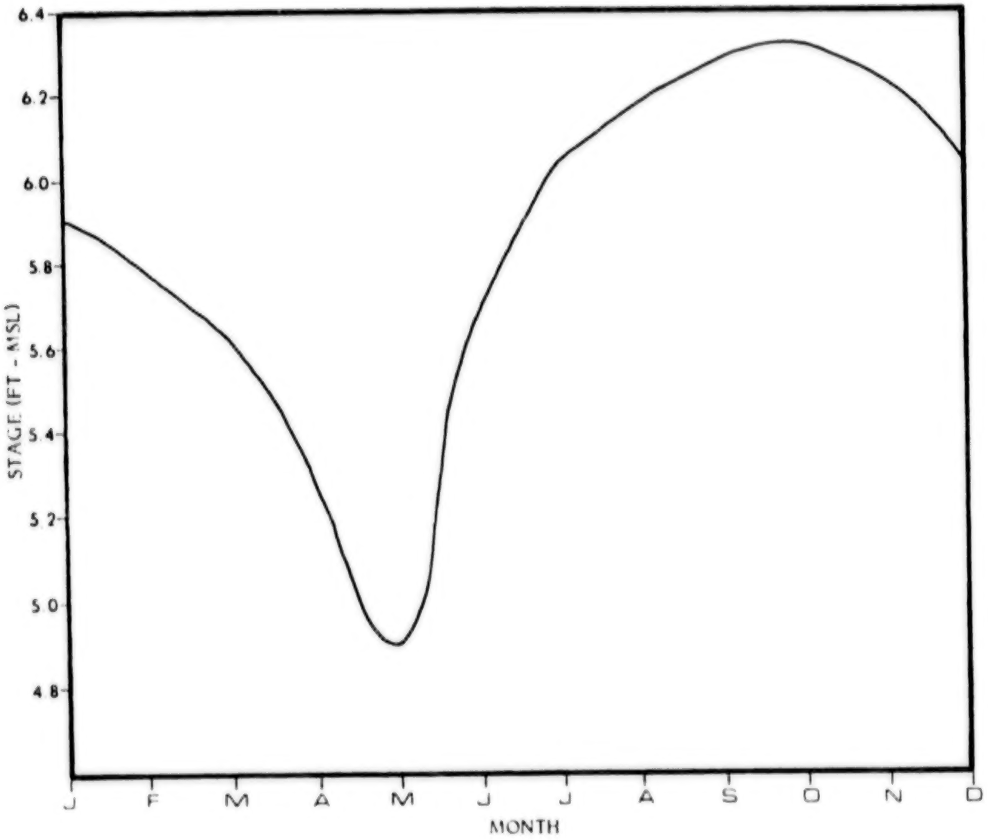


Figure 3(a). P-33 Monthly Mean Water Level, 1953-1977

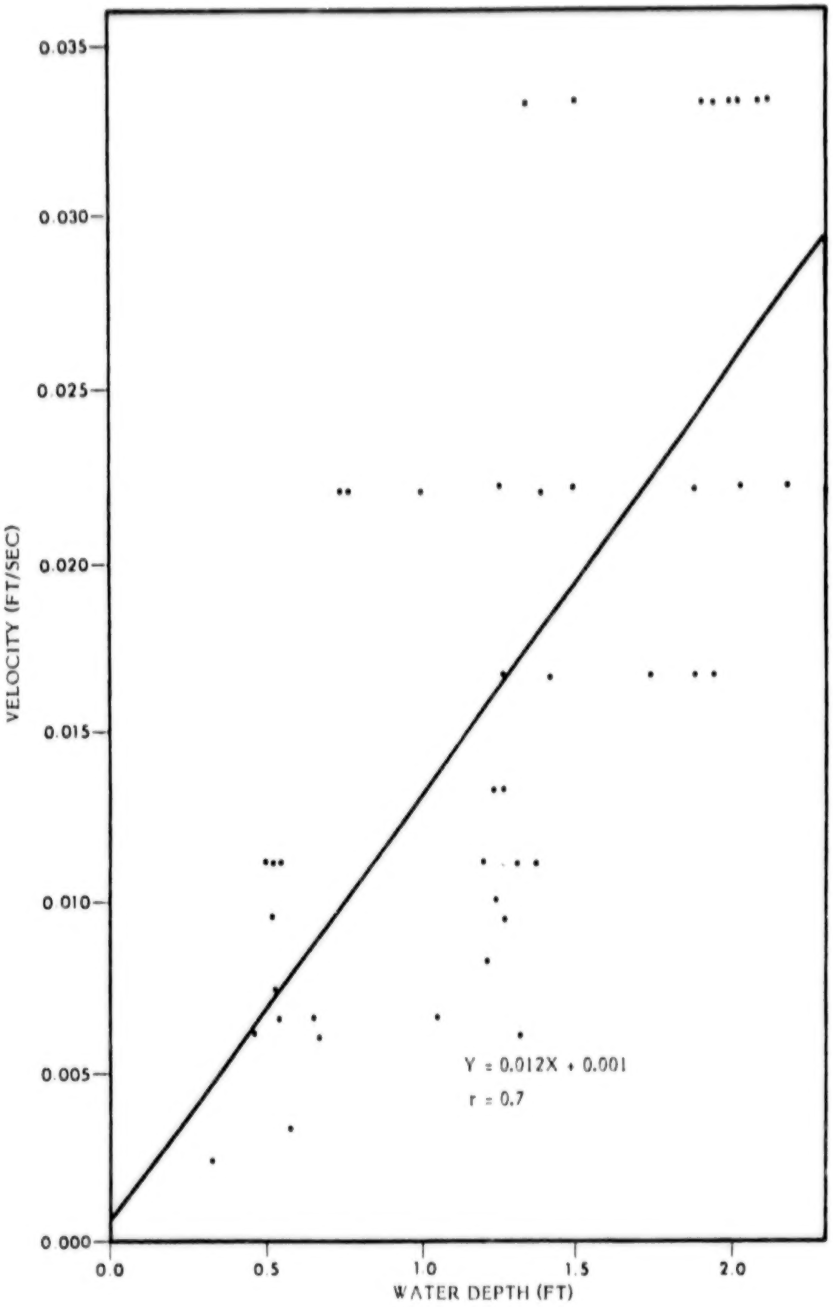


Figure 3(b). Water Depth vs. Velocity Open Marsh and Intermediate Vegetation

1979 representing 31 days of monitoring. The results of two such measurements are shown in Figure 4 for dry and wet season periods. It is seen that the slough boundary varied considerably, changing from a total width of 17 miles during the wet season to only 9 miles during the dry month of April. Cross-sectional areas were determined for each date by assuming rectangular wedges along the transect, with dimensions of station depth and one half the distance to the next station on either side of the station in question. For example, Figure 5a shows the cross-sectional area in the P-33 vicinity to be:

$$\text{Area} = wd \qquad (6)$$

Where:

d = Depth

$w = L_{1'} + L_{2'}$

$L'_1 = \frac{1}{2}$ distance to station E-100

Both L_1' and L_2' were obtained by measuring 1/2 the actual distance between P-33 and E-4 and E-100 and then projecting this distance into a plane perpendicular to the vectors as shown in Figure 5b. The results of these calculations are plotted in Figure 6a indicating crosssectional fluctuations from 25,000 to 100,000 square feet for dry and wet seasons respectively.

Flow rates along the transect were thus calculated using equation 5 from which values of 200 to 2000 cubic feet per second were obtained as shown in Figure 6b reflecting the cyclic nature of the Everglades' hydrosystem. Comparison of these data were subsequently made with flow rates past Tamiami Trail located approximately 10 miles upstream. Flow at the trail contributing to the experimental crosssection originates at the S12 flow section which consists of four gated structures and at the Northeast Shark Slough section which contains 19 culverts. Flow through the S12 structures can be determined from the rating curve shown in Figure 7a and is dependent on hydraulic head across the gates while discharges through the Northeast Shark slough section (Levee 30 to Levee 67A) is determined from a stage discharge curve wich is dependent on up-stream stage (Figure 7b). Actual flow measurements using conventional Price or Pygmy-type velocity meters are routinely taken at these flow sections through a cooperative program by the National Park Service, Army Corps of Engineers, and the U.S. Geological Survey in order to shift the rating and discharge curves as needed. Flow rates derived from these curves for comparable time periods as those of the transect are presented in Figure 8. In constructing this curve it was assumed that it took 10 days for waters originating at the Tamiami Trail to arrive at the transect. Analysis of past flood releases to the park indicated positive responses on stage hydrographs of approximately one day for staff gauges located one mile apart in the direction of flow. The transect was located 10 miles downstream of Tamiami Trail, thus a mile per day travel time resulted in a ten-day delay in transect response time to flow at the trail.

In comparing the results of transect flows with Tamiami Trail it is seen that both reflect the wet and dry flow periods of south Florida and agree fairly well. During wet periods the Tamiami Trail flow rates are higher than those for the transect and the reverse is true during dry periods. Underestimates of effective crosssectional area of the transect during the wet season could account

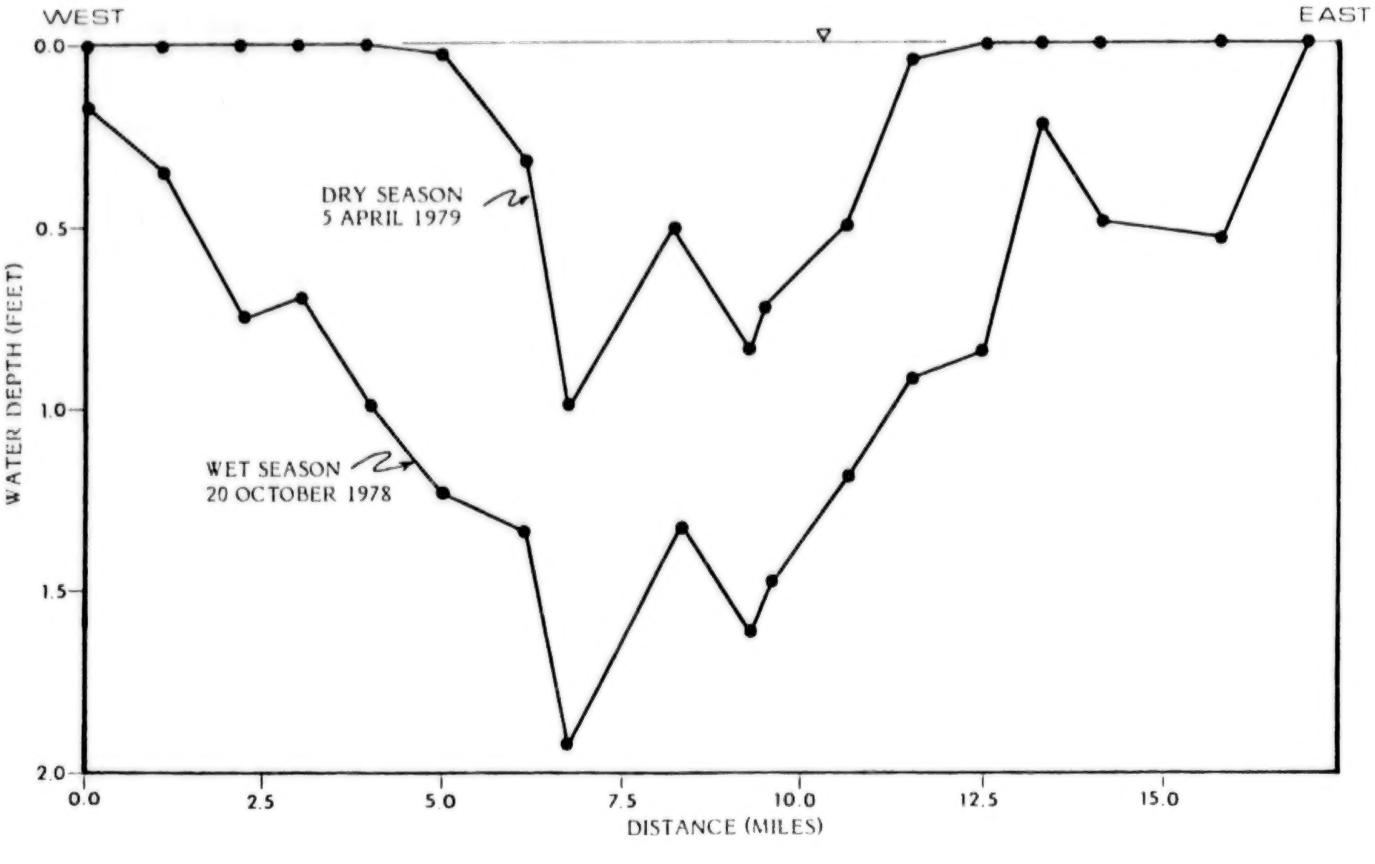


Figure 4. Shark Slough Cross-Section

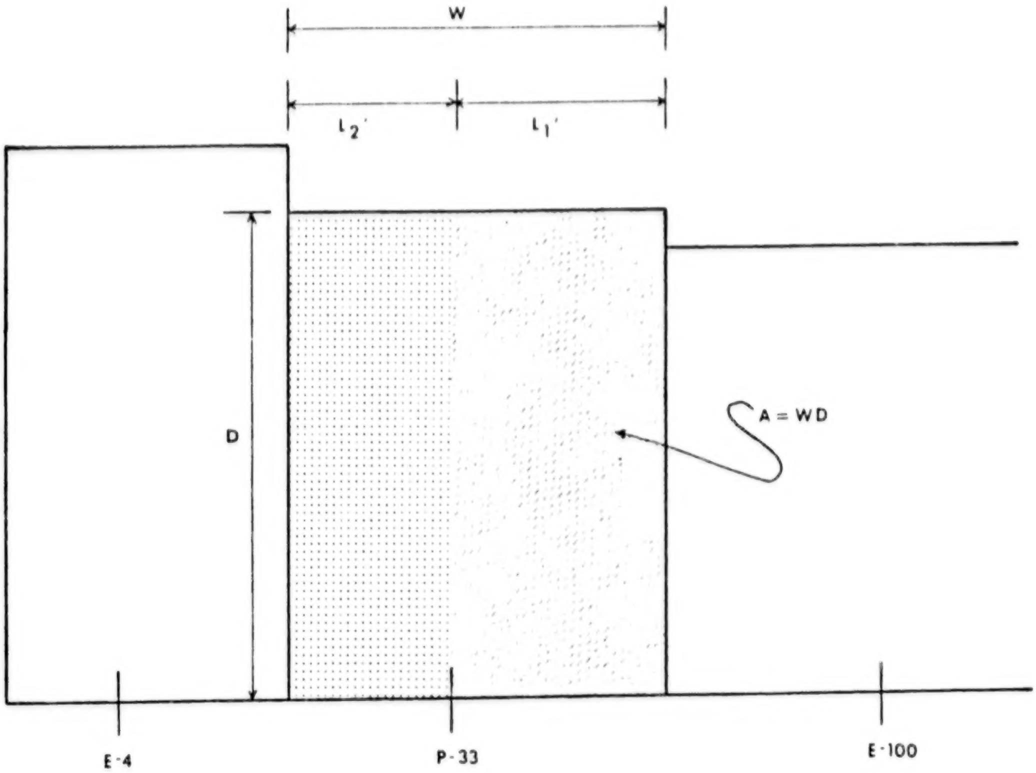
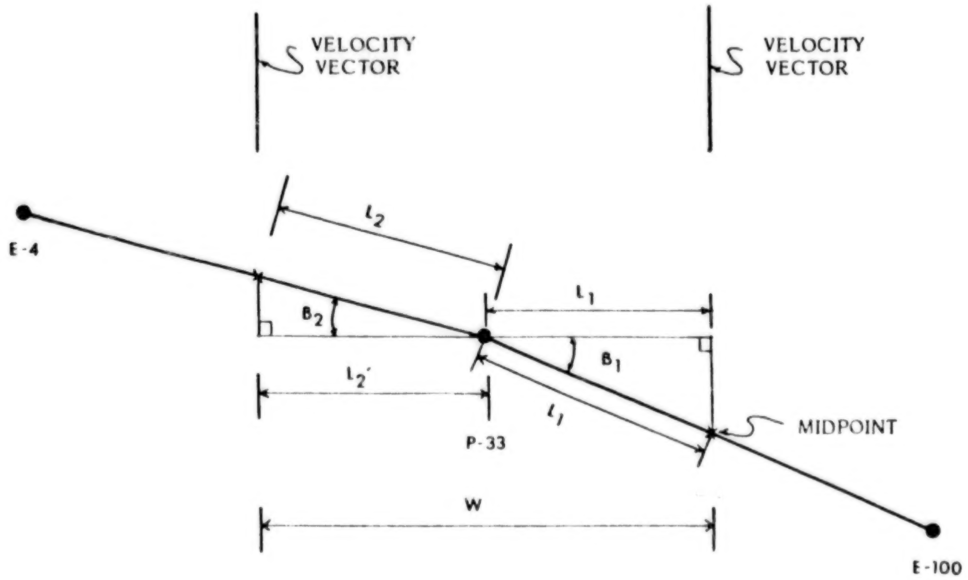


Figure 5 (a). Calculation of Cross-Sectional Area



$l_1' = l_1 \cos B_1$

$l_2' = l_2 \cos B_2$

$W = l_1' + l_2'$

Figure 5 (b). Method for Correcting Cross-Section Width

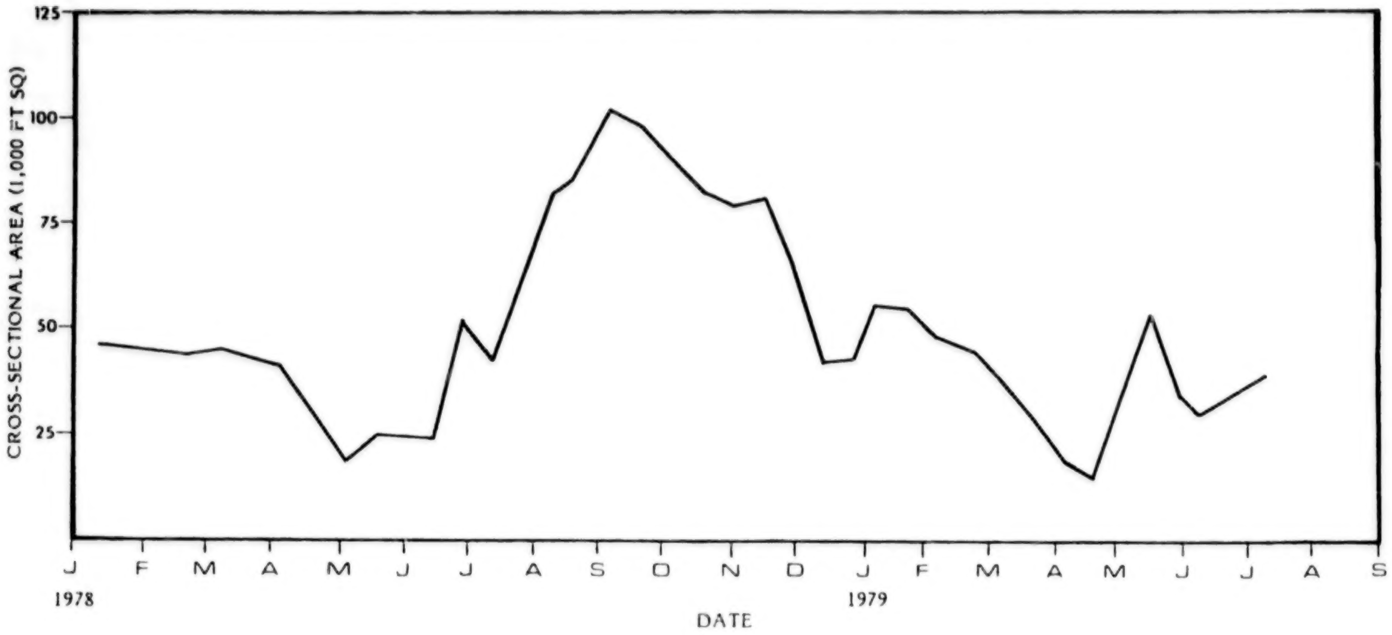


Figure 6(a). Shark Slough Cross-Sectional Area vs. Time

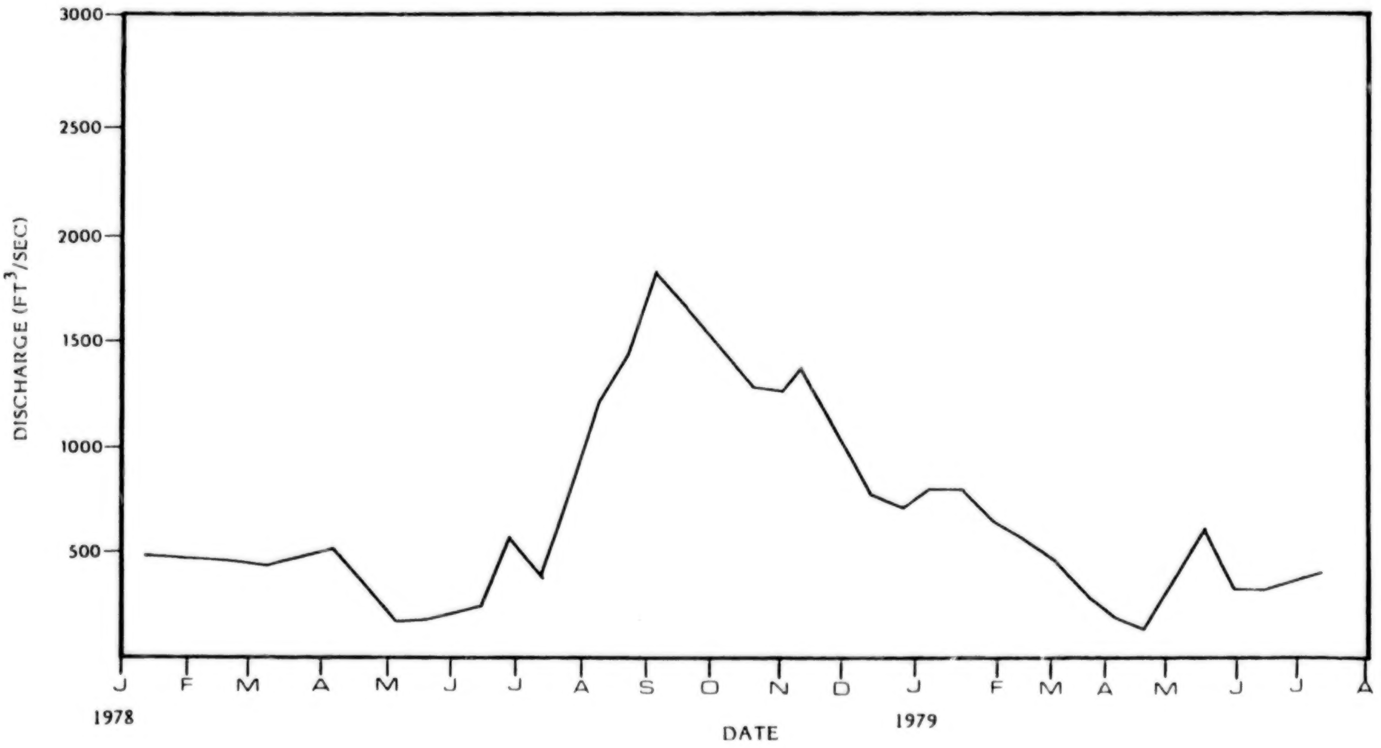


Figure 6(b). Discharge at Northern Transect (Ft^3/Sec), January 12, 1978 to July 12, 1979

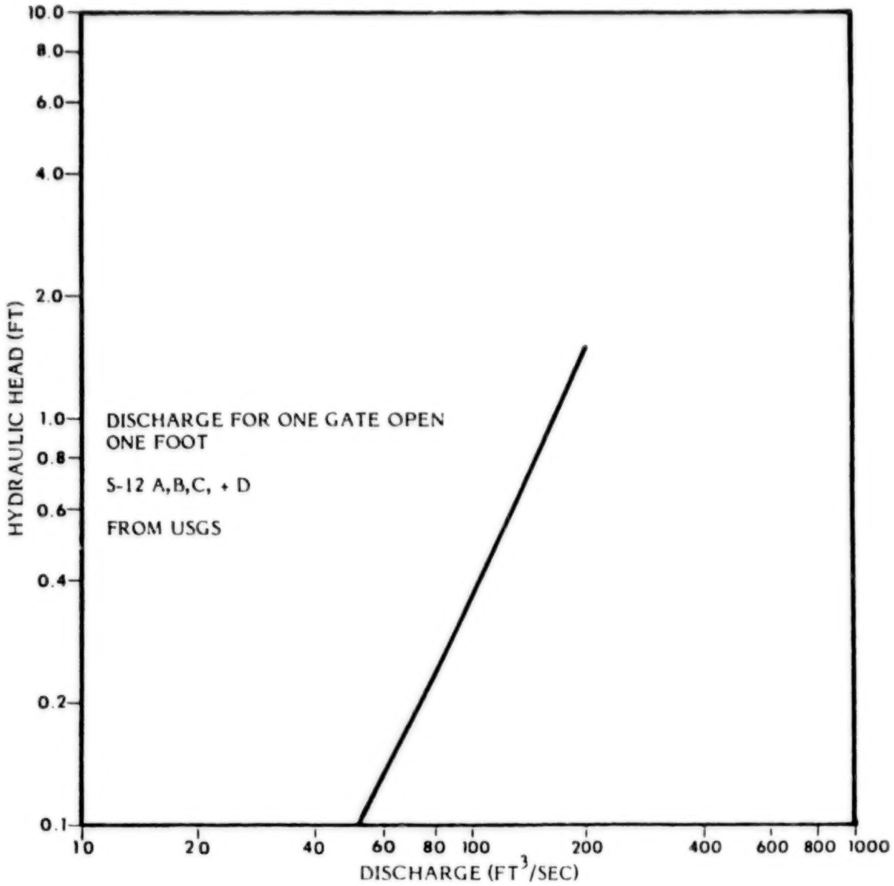


Figure 7(a). Hydraulic Head vs. Discharge at S-12 Control Structures

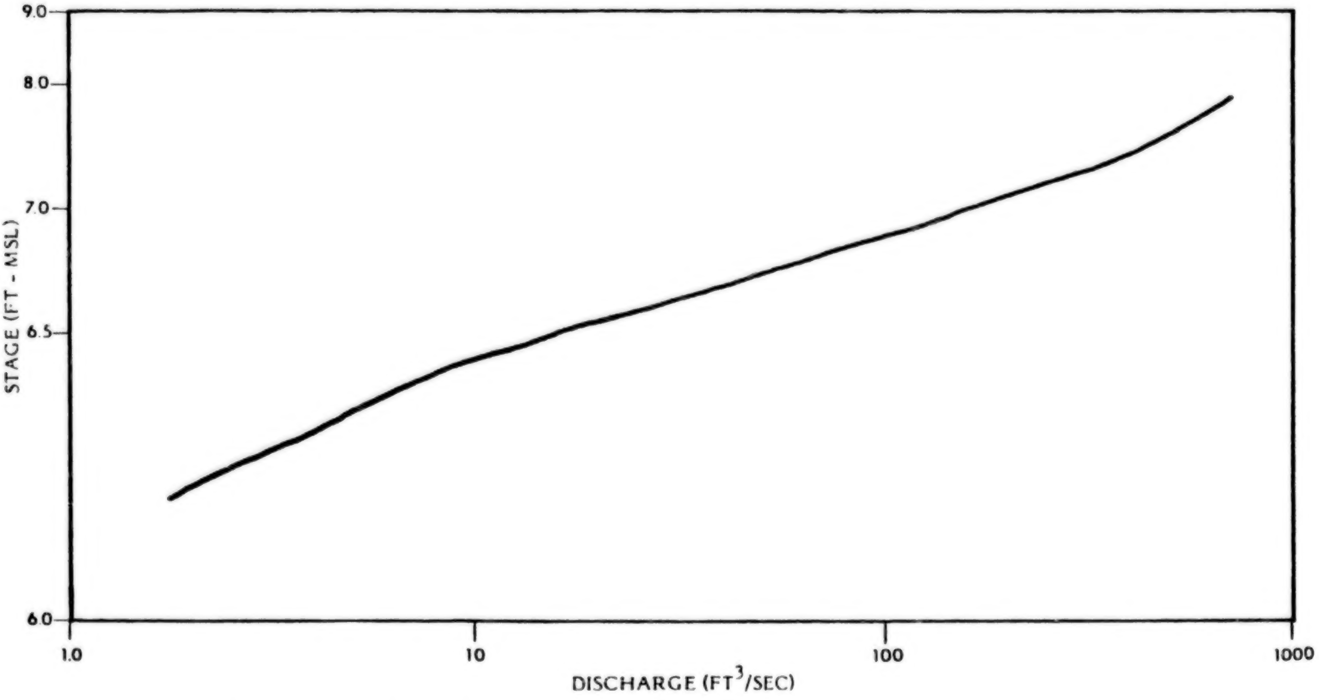


Figure 7(b). Stage-Discharge Curve for Tamiami Canal Outlets (Levee 30 to L67-A), From USGS for this discrepancy because this is the time period of the broadest extent of sheetflow and an underestimate of depth of even a few inches would greatly reduce the area due to the large width (miles) involved.

SURFACE WATER DISTRIBUTION AND STORAGE

Hydrological application of Landsat digital data for analysis of Shark River Slough surface water distribution utilized an interactive multispectral image analysis system (General Electric Image 100). Image analysis systems are based on the assumption that terrestrial features exhibit characteristic spectral reflectance patterns. Through spectral data, an image analyst can classify, map, and inventory the aerial extent of specific resources. The main purpose of digital image processing is to facilitate information extraction by producing an image that is easier to interpret, by providing statistical data about the reflectance properties of an entire scene or discrete portions of a scene, and by portraying as a separate class all features with approximately the same spectral reflectance properties.

Cloudfree Landsat scenes were acquired during both the wet and dry seasons to evaluate expansion and contraction of the Shark River Slough's marshes. Four Landsat scenes, representative of a wide range of hydrologic conditions within the slough, were selected for analysis and interpretation procedures. The October 19, 1974 Landsat scene monitored conditions during maximum inundation; while three scenes taken on March 23, 1978, April 28, 1978 and May 16, 1978 represented water conditions during a drydown period.

The main objective of image analysis for these four Landsat subscenes was to differentiate inundated and non-inundated areas within Shark River Slough. The spectral response from water bodies in all Landsat wavelength bands is characteristically low, hence appearing as dark tones on single-band images while dry lands appear as lighter tones. The land/water interface is most distinguishable on multispectral scanner Band 7 (0.8 to 1.1 m) because in this near-infrared spectral region nearly all incident energy is absorbed at the water surface. In Shark River Slough, the diffuse shallow sheet of water is heavily vegetated with sawgrass stands and open marsh vegetation. Due to the characteristic integration of spectral response over 1.1-acre areas with the Landsat multispectral scanner, the spectral response from this vegetation is averaged with the return from the underlying water surface. Hence, the spectral readings within the inundated portions of Shark River Slough will vary depending upon the respective contributions of water and vegetation within each pixel.

For each of the four selected Landsat subscenes, Band 7 data were analyzed and it was found that the October 19, 1974 scene represented maximum surface water extent compared with the May 16, 1978 scene showing minimum surface water extent (Figure 9). These results compared favorably with known slough boundaries based on field crosssectional measurements along an east/west transect.

A total of 245,427 acres were inundated during October 19, 1974 representing maximum surface water coverage in contrast to the minimum inundation for the Shark Slough totaling 90,402 acres on the May 16, 1978

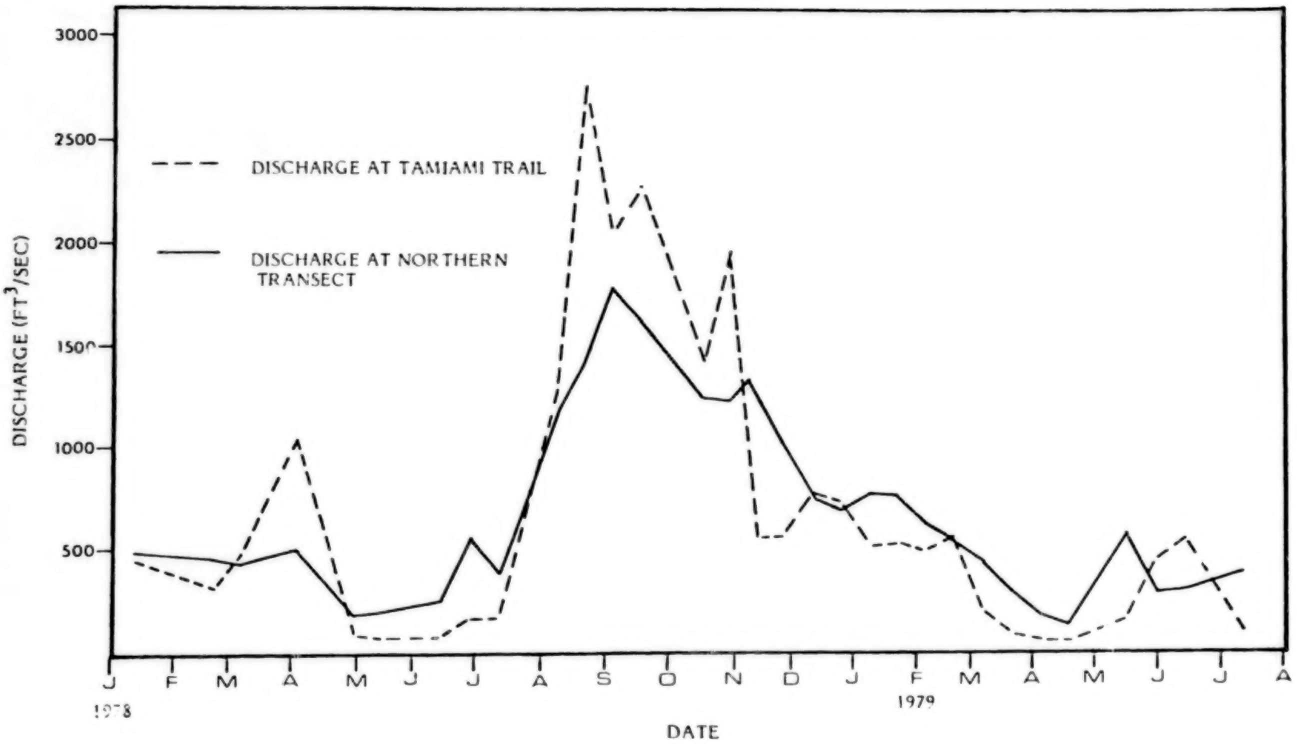
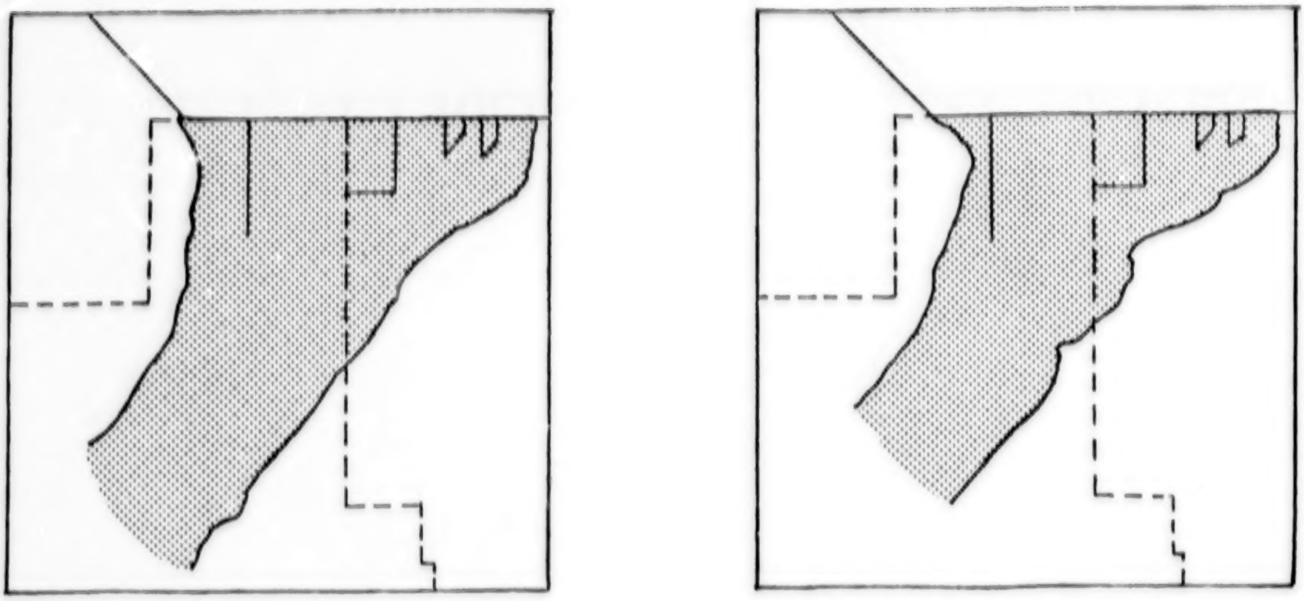
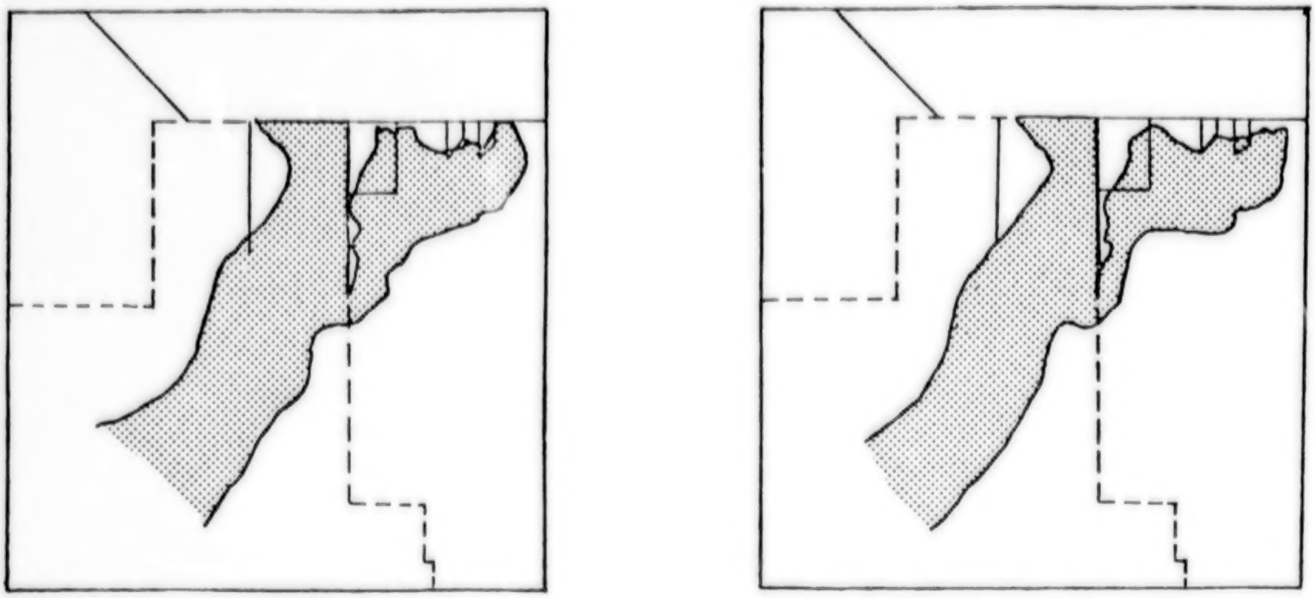


Figure 8. Discharge at Northern Transect and Tamiami Trail [Ft^3/Sec] January 12, 1978 to July 12, 1979



October 19, 1974

March 23, 1978



April 28, 1978

May 16, 1978

Figure 9. Spatial and Temporal Margins of the Shark River Slough

(Table 1). A net change of 63 percent, or 155,025 acres, occurred between the extent of surface water inundation in the Shark Slough from "wet" season to "dry" season as determined through Landsat classification.

Landsat inundation classification results were combined with water level data from hydrologic monitoring stations to estimate total water volumes for each date of Landsat coverage. The program used an interpolation technique which assigned a water depth to each "missing" pixel based on the average depth of the six closest hydrologic monitoring stations (Shepard 1968). The known water depths from each of these stations were weighted by the inverse square of the distance to each missing pixel. In this manner, water depths were calculated for each Landsat pixel within the inundation scenes.

Water volume was estimated for each Landsat subscene upon generation of water depths throughout inundated areas. To calculate water volume, the number of Landsat pixels (each representing an area of 33 x 33 feet) at each water depth was multiplied and tabulated, resulting in an estimation of total water volume for Shark River Slough on each date of Landsat coverage.

Water volume estimates ranged from 208,247 acre-feet during the period of maximum inundation to a low of 26,016 acre-feet during the period of minimum inundation representing a reduction in water volume of 87.5 percent.

The difference between the area inundated and the volume of water stored in Shark Slough between "wet" and "dry" periods is of paramount importance relating to hydrological and ecological functions in the Florida Everglades. Even though the extent of inundation changed considerably from the "wet" to "dry" seasons, the storage capability of the slough changed even more due to the relatively flat land surface and distribution characteristics.

CONCLUSIONS

Techniques were successfully developed to determine flow rates in the broad and shallow Everglades marsh within Everglades National Park. Tracer dye experiments were found to be effective in measuring low velocities characterizing the Shark River Slough. Comparison of flow rates determined for the sheet flow regime within the marsh agree with those calculated by more conventional means at upstream flow control sections. Landsat imagery allowed for the temporal quantification of aerial and volumetric contraction and expansion of surface waters in the Everglades marsh. Seasonal effects within the South Florida hydrologic cycle were reflected by as much as a 63 percent reduction in inundation area and 87.5 percent reduction in volumetric surface water stored between the "wet" and "dry" seasons. Such shifts in available surface water storage play a significant role in driving the productivity of the Everglades ecosystem.

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Table 1. Inundated areas of surface water and estimated water volumes stored in Shark River Slough as determined from Landsat data.

Date	Acres Inundated	Estimated Volume
19 October 1974	245,427	208,247 acre-feet
23 March 1978	163,108	107,715 acre-feet
28 April 1978	123,426	52,416 acre-feet
16 May 1978	90,402	26,016 acre-feet

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EFFECTS OF UPLAND DRAINAGE ON ESTUARINE NURSERY AREAS OF PAMLICO SOUND, NORTH CAROLINA

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ABSTRACT

Four sampling stations were established in tributaries of northern Pamlico Sound, N. C., to measure the effects of upland drainage on primary nursery areas. The four stations received either heavy, moderate, or no drainage through man-made water courses. All stations functioned as primary nursery areas during periods of low rainfall and high salinity (1977). Brown shrimp production at all sites was depressed during periods of extremely high rainfall and low salinities (1978). Salinities at the unaltered sites were more stable during periods of high runoff than those recorded at two sites receiving drainage through ditches. Recovery times at the altered sites were approximately 10 days. The most significant reduction in production of juvenile brown shrimp occurred at the extensively ditched site during periods of moderate to heavy rainfall.

INTRODUCTION

The North Carolina Division of Marine Fisheries began identifying, in 1970, areas of the sounds and bays in the coastal region of North Carolina which serve as nursery areas for economically important species of fish and shellfish. The most productive and the most sensitive of these areas were subsequently classified as "primary nursery areas." Regulations were adopted which gave the primary nursery areas special consideration for limiting commercial fishing activity and protection from alteration through dredging and filling (N. C. Administrative Code 15NCAC 3b. 1400 *et seq.*). Primary nursery areas were found to be, characteristically, the upper reaches of small tidal creeks which have soft mud sediments, are surrounded by regularly or irregularly flooded marshes, and have salinities ranging from five to fifteen parts per thousand (ppt).

Data collected over a four-year period prior to this study indicated the primary nursery areas which were receiving upland drainage through man-made ditches and canals had less stable salinity patterns and were relatively less productive than creeks with unaltered drainage basins. This encouraged a more thorough investigation of the impacts of freshwater drainage into primary nursery areas on the production of brown shrimp (*Penaeus aztecus*).

Estuaries are those areas where salt water and fresh water mix to form an environment in which salinities range from near 0 to about 15 ppt. These areas in North Carolina possess a variety of other physical characteristics such as size, depth, bottom type, bottom vegetation and bordering vegetation which influence the types and numbers of organisms a particular sound, bay, or creek will produce. It appeared from preliminary sampling that another variable (accelerated freshwater drainage) was also affecting this productivity.

The history of land clearing and drainage in low lying areas of coastal North Carolina began with the first settlers of the region about 1770. However, conversion of large areas of woodland into agricultural production did not begin until the technology was available to economically clear and drain low-lying areas on a large scale. This problem is particularly prevalent in the large peninsula lying between Albemarle Sound and Pamlico Sound in northeastern North Carolina. Extensive conversion of forest land to farm land in this area, with the associated drainage into both sound systems, has led to speculation that changes in water quality could be the most serious future impact from this type of development. Drainage of the Albemarle Sound peninsula has proceeded by using a system of canals and field ditches as described by Heath (1975). The nearest natural water bodies to receive drainage from these systems are often those identified as primary nursery areas. Heath indicated in his report that runoff from the Albemarle/Pamlico peninsula could be the most important problem posed by agricultural development. Heath also explained that overall salinities in the Pamlico Sound will probably not be significantly affected by runoff from this region because it contributes such a small proportion (6.8%) of the total freshwater inflow. A more dramatic effect on salinities would occur with drainage into the smaller streams and bays.

Prior studies on the hydrology of the Pamlico Sound region have dealt with the large open water areas. Our attention in this study was focused on the lateral estuaries, which comprise a large and important part of the total Pamlico Sound system.

MATERIALS AND METHODS

This study began in 1977 with the selection of three sampling areas to compare salinity patterns and habitat utilization between areas with natural drainage patterns and areas receiving drainage through man-made waterways. Each site was selected to provide, as nearly as possible, only one variable, freshwater inflow through ditches. There were, however, some differences in water depth and bottom types among the stations. The extent to which these differences affected overall productivity are not known. A fourth station was added in 1978 to give an equal number of altered and unaltered locations in the study. The sampling stations are shown on Figure 1 and designated A-1 and A-2 for the altered areas, and U-1 and U-2 for the unaltered areas.

Recording salinometers were installed at three sites (A-1, A-2 and U-1) to continuously record

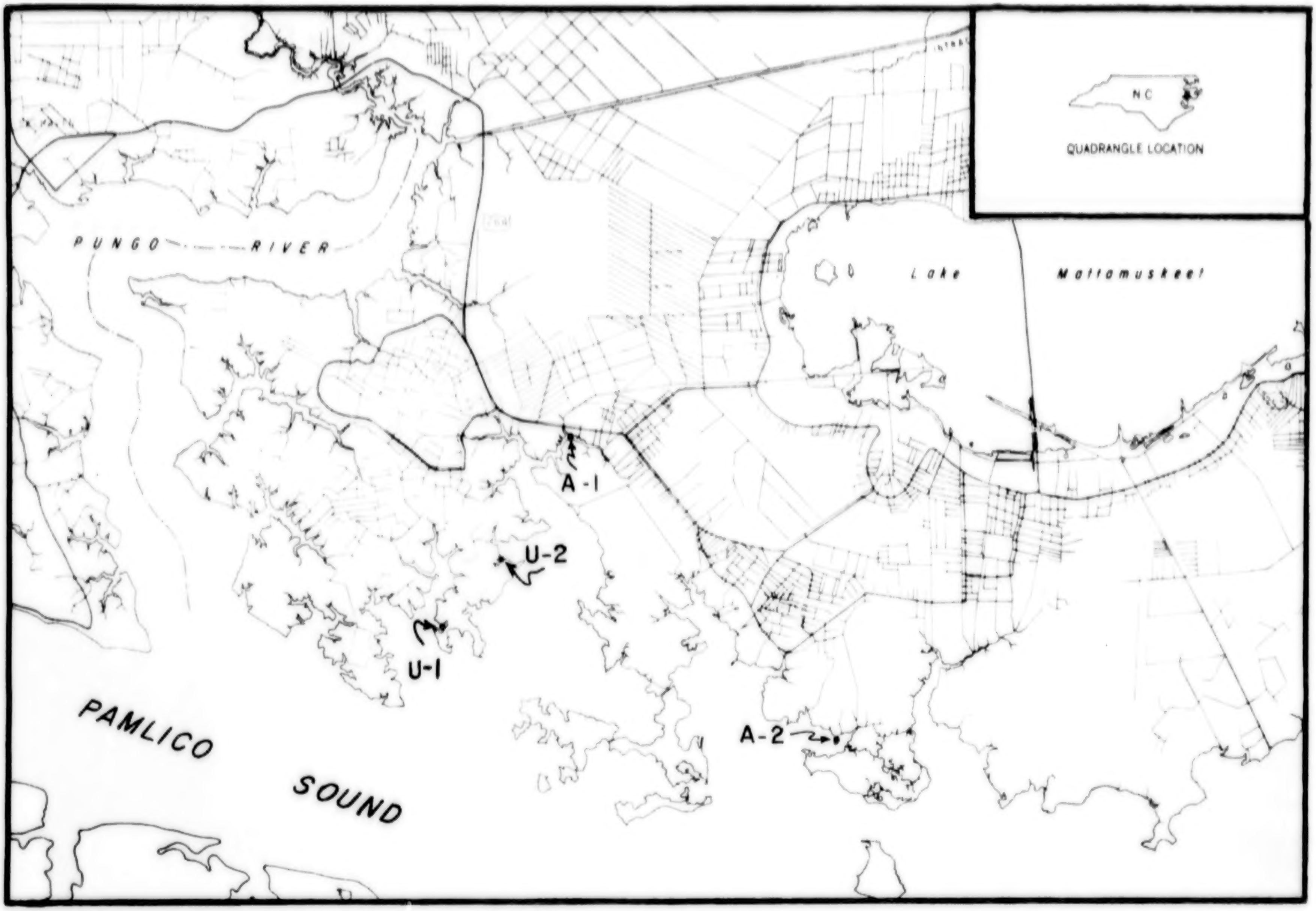

Figure 1. Location of study area, sampling sites and ditches draining into tributaries of northern Pamlico Sound.

salinity changes. Salinities were recorded approximately 12 inches from the bottom because bottom salinity changes would have the most effect on utilization of the area by juvenile shrimp which are characteristically found in the substrate. Weather instruments were installed within the Rose Bay drainage system to record wind direction, wind speed, and rainfall. A tide gauge was installed to constantly measure tidal fluctuations within Rose Bay.

Sampling was conducted at two locations within each sampling area to identify movement of organisms responding to freshwater inflow. Data from these stations were later combined when it was shown that there was no significant difference between the numbers of organisms sampled at the two locations. Each station was sampled with a 13-ft (3.96-meter) headrope, flat otter trawl with a 0.25 in (0.64-cm) bar mesh knotted wings and body, and a 0.25 in bar mesh knitted tail bag. Each sample consisted of towing this trawl a measured distance of 45 meters between fixed markers. Salinity and temperature recordings were taken with each sample with a portable meter to later verify readings by the recording salinometers. Each station was sampled three times a week during the shrimp season (May through July). Each sample was preserved in the field and recorded in the laboratory. All species of organisms taken were identified and measured.

Figure 1 is a reproduction of a map prepared by the U. S. Geological Survey showing the location of all drainage ditches in the Albemarle/Pamlico Sound peninsula as of 1978. This map will give some indication of the number of drainage ditches going into each of the areas sampled, and the size of the area which is being drained.

Station A-1 (Rose Bay Creek) has a number of small ditches draining individual farms, and one large canal used as a water control outlet for management of Lake Mattamuskeet. Rose Bay Creek is bordered on each side by a marsh area dominated by black needlerush (Juncus roemerianus) and saw grass (Cladium jamaicensis). Water depths range from 2 m to 3 m and the bottom type may be characterized as muddy and overlain with coarse organic detritus.

Station A-2 (Caffee Bay) also receives drainage from an extensive inland area. The main differences between this location and Station A-1 are that flow into this nursery area is confined to two main ditches which have to drain through an extensive bordering marsh of black needlerush. There are four additonal ditches draining into Caffee Bay which terminate in the adjacent wetland area and do not appear to carry any non-wetland drainage. Water depths at this site range from 1 m to 1.5 m and the bottom type is a mixture of soft mud and detritus.

Station U-2 is also surrounded by a large expanse of black needlerush marsh and a low-lying pocosin vegetated with pond pine. Figure 1 shows that there are two ditches entering the headwaters of this creek. However, these ditches do not carry drainage from any non-wetland areas; therefore, the creek was considered as being unaltered. Water depths ranged from 0.3 m to 1.3 m and the bottom type is a mixture of deep mud, detritus, and marine shells. This is the only station which did not have a 24-hour salinity recorder.

RESULTS AND DISCUSSION

Organisms which inhabit the low to medium salinity estuaries have developed the ability to adapt to an environment which is naturally stressful. Sudden fluctuations in temperature, salinity, turbidity, and nutrient levels reduce the number of species which can adapt to these stresses and take advantage of conditions conducive to high levels of productivity. Those that do adapt usually flourish during periods of peak productivity.

One major stress to organisms studied is rainfall and the consequent changes in salinity. Salinity patterns in this area are largely influenced by the amount of rainfall over a given period, the effects that wind and tidal fluctuations have on the distribution of brackish water, and the nature of the drainage basin. Total freshwater inflow from natural drainage basins within the Albemarle/Pamlico peninsula is not significantly changed by man's use of the drainage basins. However, development has changed the rate of freshwater discharge into the receiving waters. A typical ditching system used in this area to prepare land for development is designed to efficiently remove surface water from the cultivated fields. These extensive collection systems increase peak runoff rates and alter the ability of the inland areas and associated vegetation to act as a natural regulator of surface runoff. The results are an increase in the rate of runoff during and following storms and an unstable salinity pattern responding quickly and dramatically to rainfall. Heath (1975) reported increases in runoff during fair weather also because the ditches and canals penetrate the shallow ground water system.

When this study was designed, I had hoped to correlate juvenile shrimp movement in response to freshwater inflow. This would have required a study period with high salinity during larval recruitment, thereby allowing good utilization of the nursery areas. Any movement from the nursery areas could then be detected with frequent sampling and related to continuous salinity recordings and rainfall data. We were never afforded a set of ideal conditons, however, to say definitely that migration occurred as a result of rapid freshwater runoff. In fact, we had a range of rainfall conditions from extremely dry in 1977 to extremely wet in 1978. Table 1 gives the annual rainfall for a three-month period which was considered to be the most critical period to have optimum conditions in the nursery area environment. This is the time (April-June) when larval shrimp will leave the inlets and migrate inland in search of suitable habitat to begin their development. Also shown is the total commercial harvest of shrimp for each year except 1980.

Total rainfall at the recording station for the period April 1 through June 30 for 1978 was 18.91 inches. Peak salinities at the four sampling stations from May through July of that year ranged from 3 ppt to 7 ppt as compared to 1977 readings of 10 ppt to 17.6 ppt for the same period when rainfall was only 7.23 inches. Rainfall during 1978 was sufficient to lower salinity levels at all stations during periods of peak recruitment. Catches of juvenile shrimp in 1978 dropped 9.3 percent to 10 percent at the four sampling stations when compared to 1977 samples. Nursery area sampling throughout the entire region in 1978 reflected the lowest level of

Table 1. Total rainfall (April-June) and commercial shrimp harvest for each year 1977-1980.

	Total rainfall (inches)				Shrimp harvest lbs. heads off
	April	May	June	Total	
1977	1.87	3.36	2.00	7.23	3,480,877
1978	7.80	7.79	3.32	18.91	1,834,687
1979	4.33	6.13	2.37	12.93	3,801,822
1980	3.00	2.97	6.72	12.69	not available

juvenile recruitment ever recorded. Commercial harvest for that year was a record low of 1,834,687 pounds heads off. Rainfall in 1979 and 1980 during recruitment periods was more normal than the preceding two years and nursery area sampling showed a more normal trend. Commercial harvest in 1979 was 3,801,822 pounds; landing data for 1980 are not yet available, but it appears that landings will equal or exceed those for 1979.

The dry sampling period in 1977 gave the opportunity to establish that all the sampling areas can function as valuable nursery areas when salinity conditions are suitable. This was particularly important with regards to Station A-1 which is the most altered system. Sampling prior to this study showed that Rose Bay Creek could be considered only marginally productive with regards to total number of organisms sampled, and no effort was made to correlate the catches with salinity levels. Sampling in 1977 at A-1 yielded catches of juvenile brown shrimp equal to or exceeding those at every other station.

Results from salinity readings show that there is a marked difference between the relative stability of salinity levels between the altered and unaltered study areas. Figure 2 is a graph of salinity readings taken at the three recording points over a 24-hour period on May 21, 1980. A 2.26-inch rainfall, accompanied by 20 to 30 mph southeasterly winds, was recorded during the same period. Salinities ranged from 5 to 7 ppt among the three recording points prior to the rainfall. The unaltered drainage basin (U-1) shows clearly the most stable salinity pattern. Salinity readings dropped sharply from 6.5 to 5.8 ppt, but recovered quickly to stabilize at 6.5 ppt within 24 hours. Salinity readings at the two recording stations within altered drainage basins showed rapid pulses in salinity levels during this period. The pulses had a frequency of approximately 1.5 hours and a range as wide as 2.5 ppt. Salinity readings at A-2 quickly stabilized at approximately 6.5 ppt once the rains ended. Salinities at Station A-1 continued their erratic pattern.

I would have expected a response in salinity changes due to rainfall to have been a rapid, but steady decline. The extremely erratic pattern of salinity changes shown in Figure 2 cannot be expained. It was, however, characteristic of salinity readings at Station A-1 throughout the recording period, except during extended periods of no rainfall. One would expect the stresses on osmoreguation by organisms to be severe during these periods of rapid salinity fluctuation.

Heavy rainfall, spread over the entire drainage basin of a tributary, influenced salinity levels in the tributary for days after the actual rain. The extent and frequency of salinity fluctuations depended upon the control over tide levels exerted by wind direction and wind speed. Northeasterly winds in Pamlico Sound tend to increase tide levels and retain surface waters in the field ditches, thereby reducing the effect on salinities in the receiving waters. Southwesterly winds, conversely, tend to lower tide levels and pull water out of the drainage ditches into the receiving waters. Tide fluctuation shown in Figure 3 shows that the

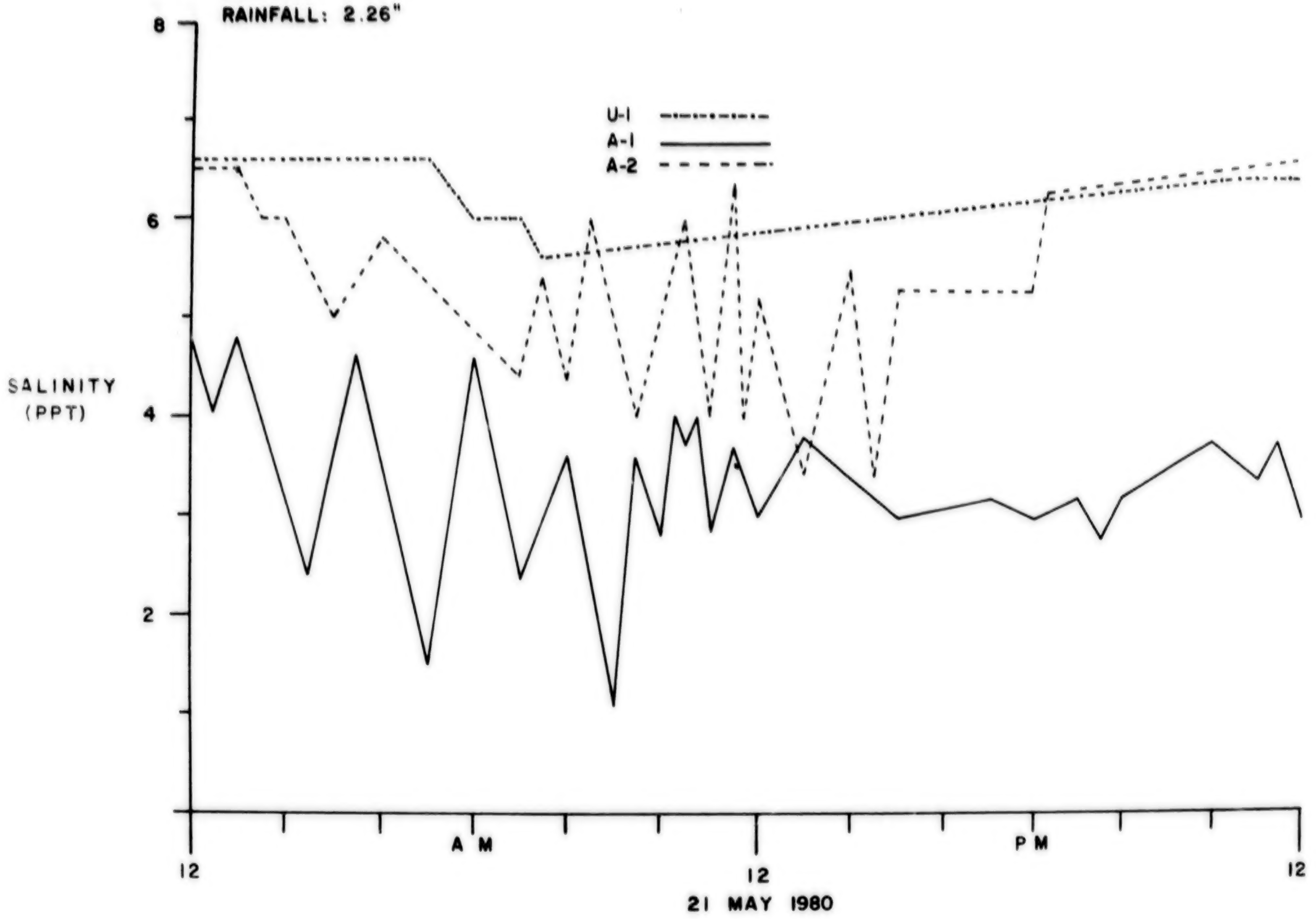

Figure 2. Graph of salinity readings at three sites over a 24-hour period on 21 May 1980. (U=unaltered; A=altered).

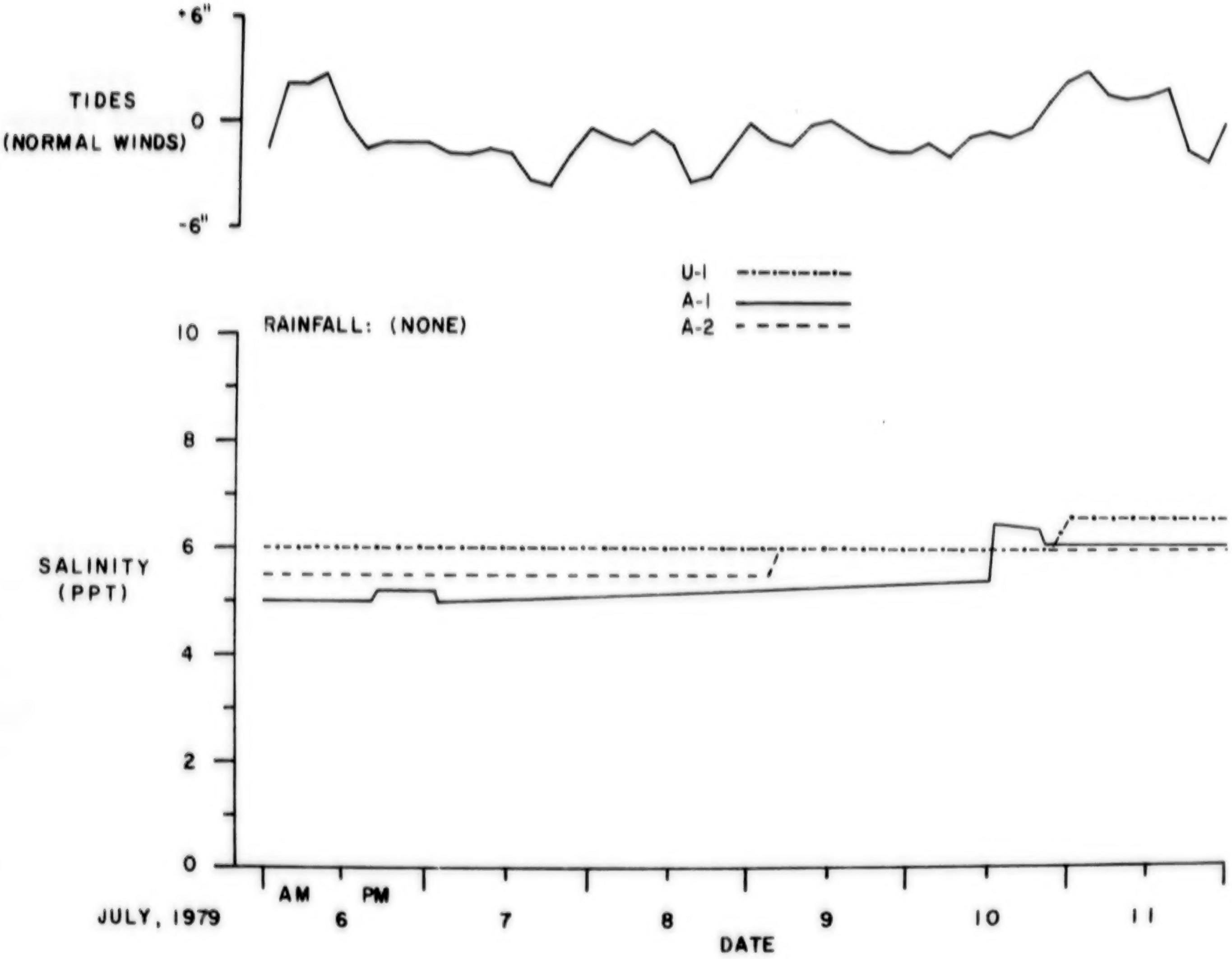

Figure 3. Tide fluctuations and salinity patterns during a period of no rainfall, 6 July - 11 July 1979.

effects of lunar tides in the sampling area are clearly masked by the influence of winds and distance from inlets to the Atlantic Ocean. Figure 3 also shows that changes in tide levels during this period with no rainfall did not affect salinity levels at the recording stations.

Figure 4 is a record of tide levels and salinity recordings for the period 20 July through 25 July 1979 when a total of 2.99 inches of rainfall was recorded. Salinity patterns for the period immediately proceeding that shown in Figure 4 were normally affected by light rainfall and changes in tide levels. During the period of extensive rain, covered by Figure 4, salinity readings show a constant depression due probably to the complete saturation of the basin and a constant runoff of fresh water. In this situation, changes in tide levels had no recognizable effects on salinity.

Catch data during the period covered by Figure 4 did not indicate any unordinary movement of shrimp at Stations A-2 and U-1 during that period. The catches during this period were small (8 to 19 shrimp per trawl), however, and significant natural migration from the nursery areas had occurred in mid- to late June (Figure 5). Migration from Station A-1 was nearly complete at this time; therefore, the impacts on shrimp could not be determined.

Catches of juvenile brown shrimp normally peaked during the period late May to mid-June (Figures 5 and 8). Recruitment into Station A-1 was later than at the other locations. This was most apparent during the years 1979 and 1980 when recruitment was generally good and rainfall was light during the recruitment period. Recruitment times for these two years at Station A-1 also correspond with periods of higher and more stable salinities (Figures 4 and 8).

Total species composition at the four sampling stations was basically the same for each year. Samples yielded a total of eleven species of fish and crustaceans. Spot (Leiostomus xanthurus), menhaden (Brevoortia tyrannus), and brown shrimp were the three dominant species each year during the period sampled at all sampling sites.

A comparison of total numbers of individuals caught as a measure of relative productivity showed that Station A-1 consistently produced the fewest organisms. Station U-2 was consistently the most productive. The year of lowest productivity was 1978 when rainfall was high and salinities were depressed. Species more characteristic of freshwater environments, alewife (Alosa pseudoharengus) and white perch (Morone americana), occurred at all stations that year. This was the only year white perch were captured. Conversely, weakfish (Cynoscion regalis) and spotted seatrout (Cynoscion nebulosus) occurred only during 1977 when salinities were high.

CONCLUSIONS

1. Drainage of surface water from upland areas into nursery areas through man-made ditches and canals creates unstable salinity conditions when rainfall exceeds 1 inch in a 24-hour period. The unaltered nursery areas showed much more stable salinity readings during the same rain periods.

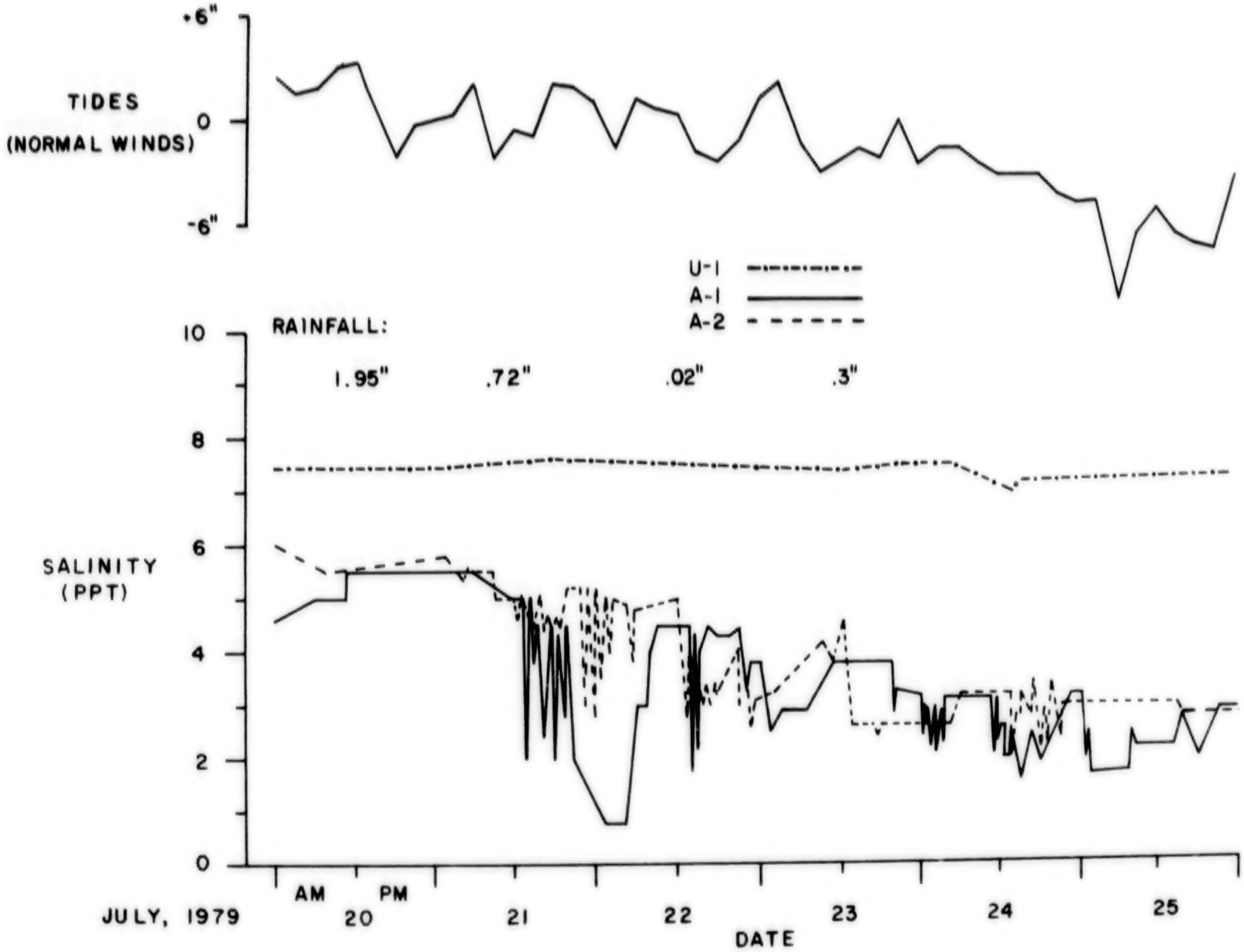

Figure 4. Tide fluctuations and salinity changes during a period of heavy rain, 20 July - 25 July 1979.

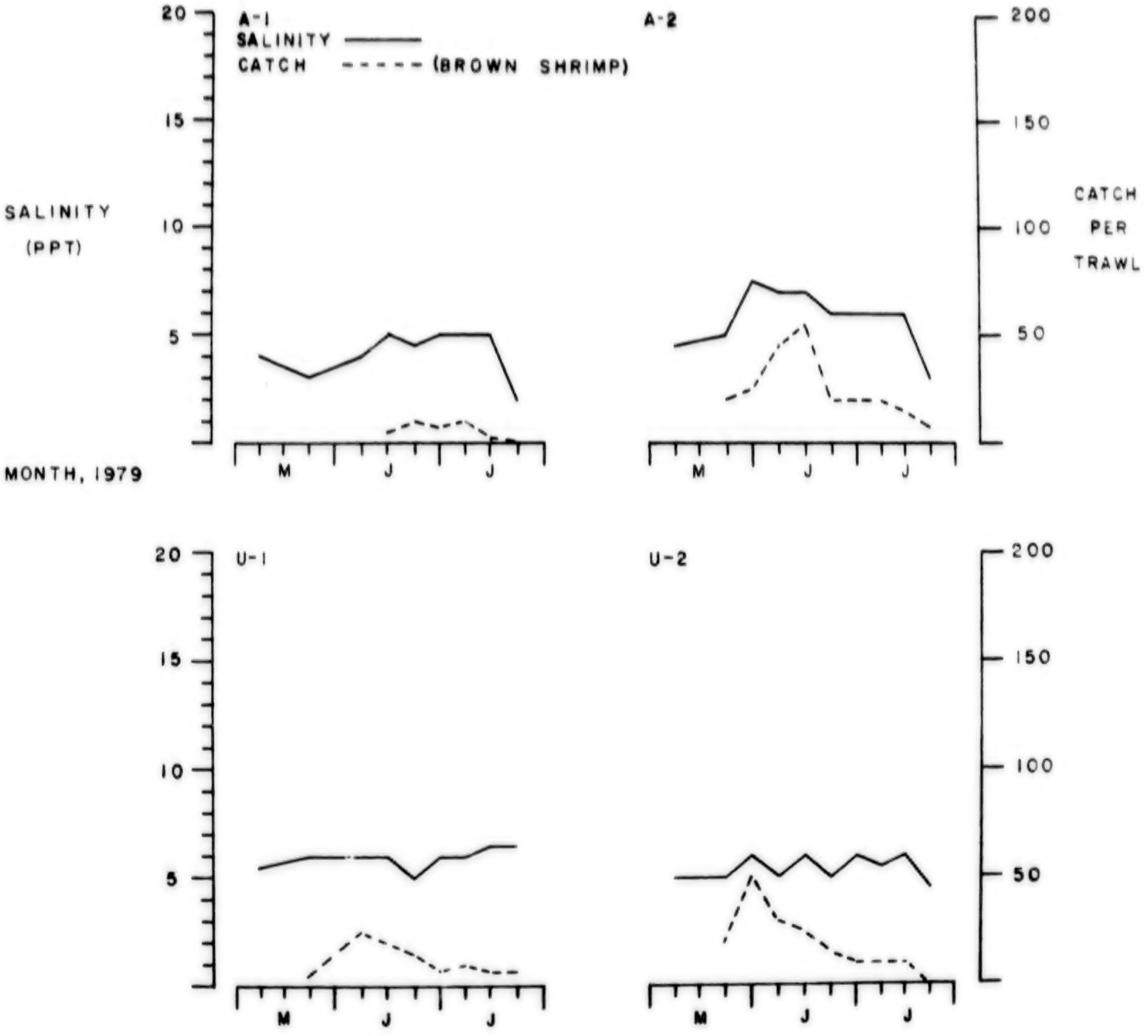

Figure 5. Weekly salinities and catch per trawl of juvenile brown shrimp (Peneaus aztecus) at four locations in 1979.

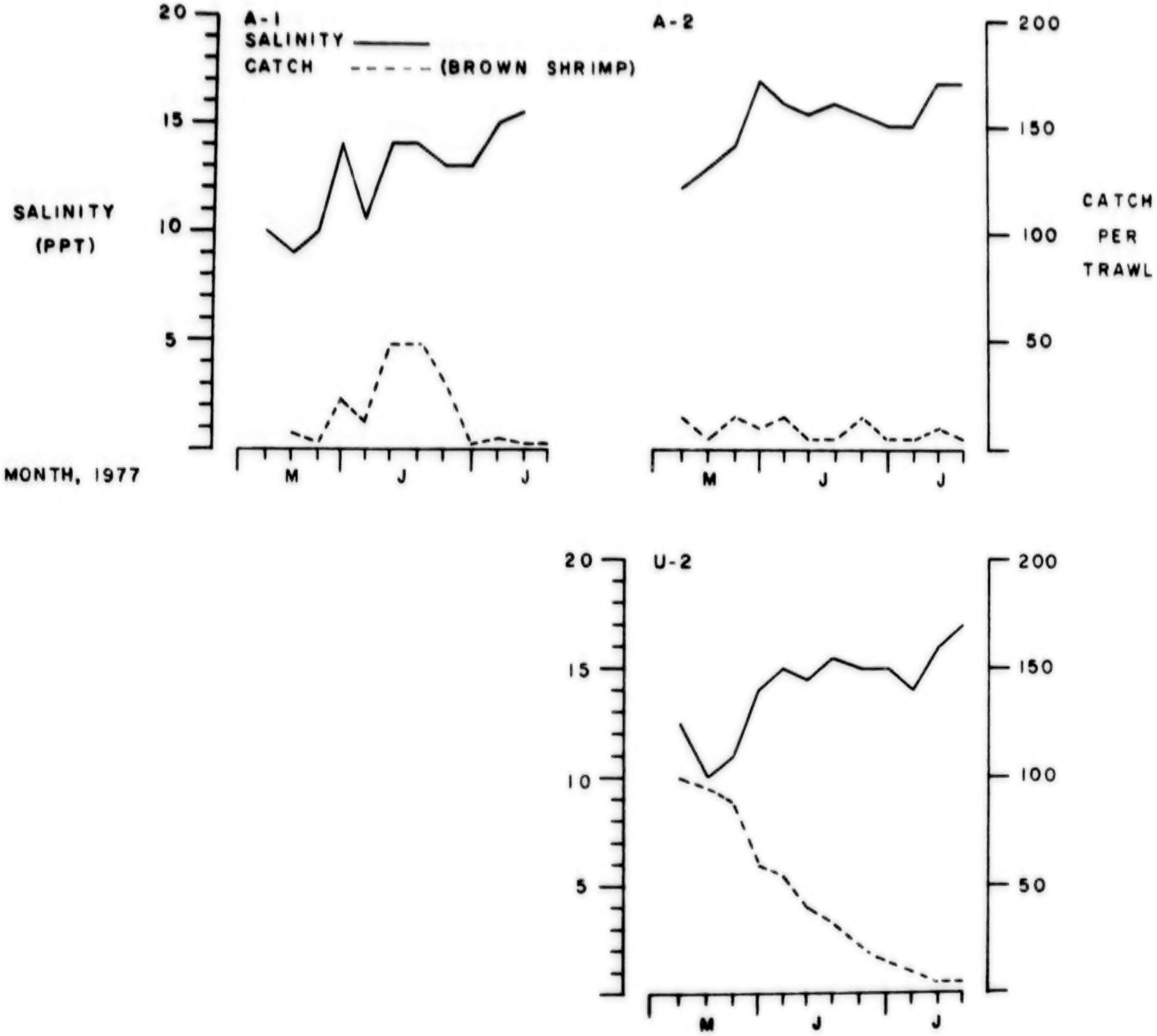

Figure 6. Weekly salinities and catch per trawl of juvenile brown shrimp (Peneaus aztecus) at three locations in 1977.

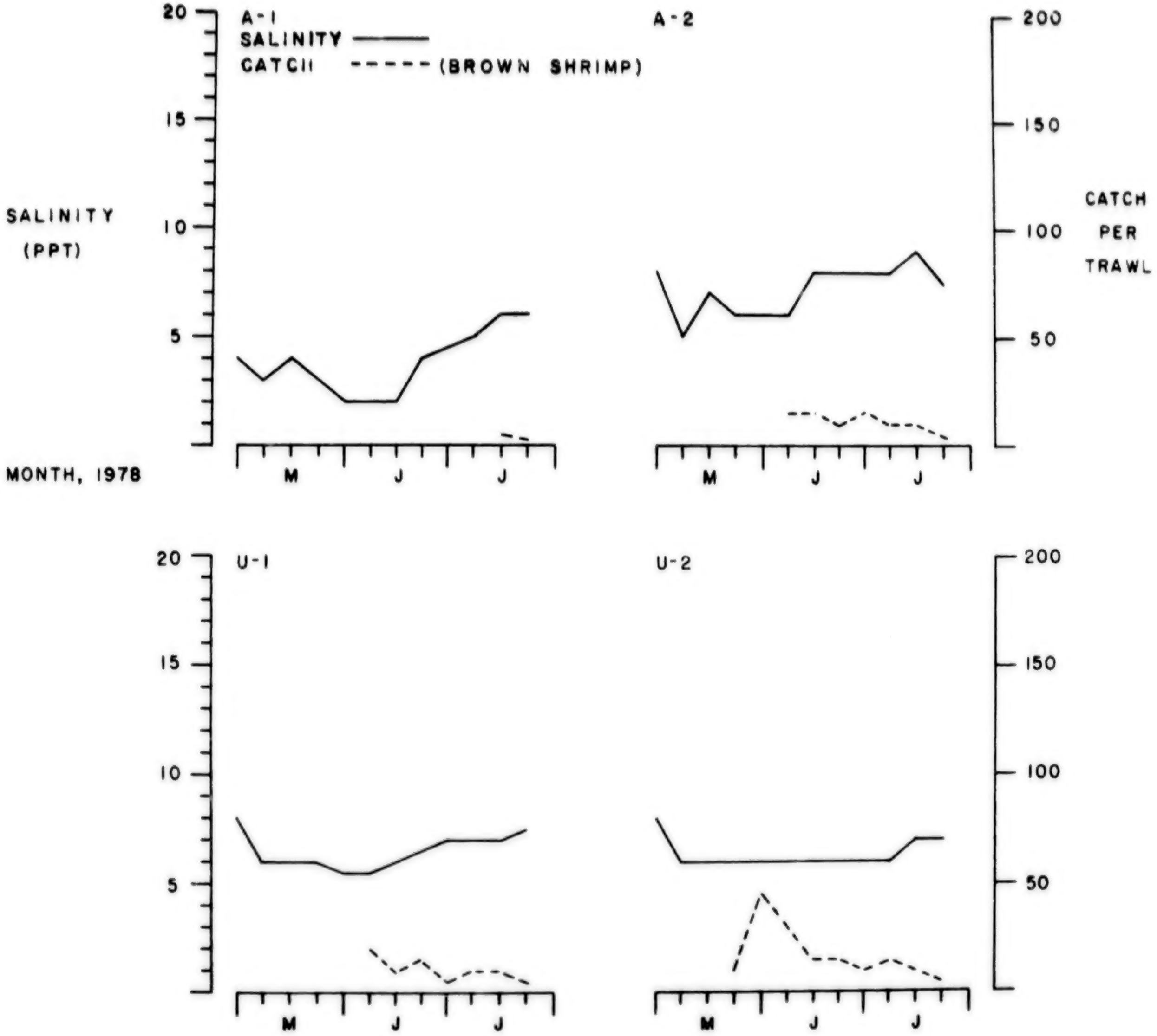

Figure 7. Weekly salinities and catch per trawl of juvenile brown shrimp (Peneaus aztecus) at four locations in 1978.

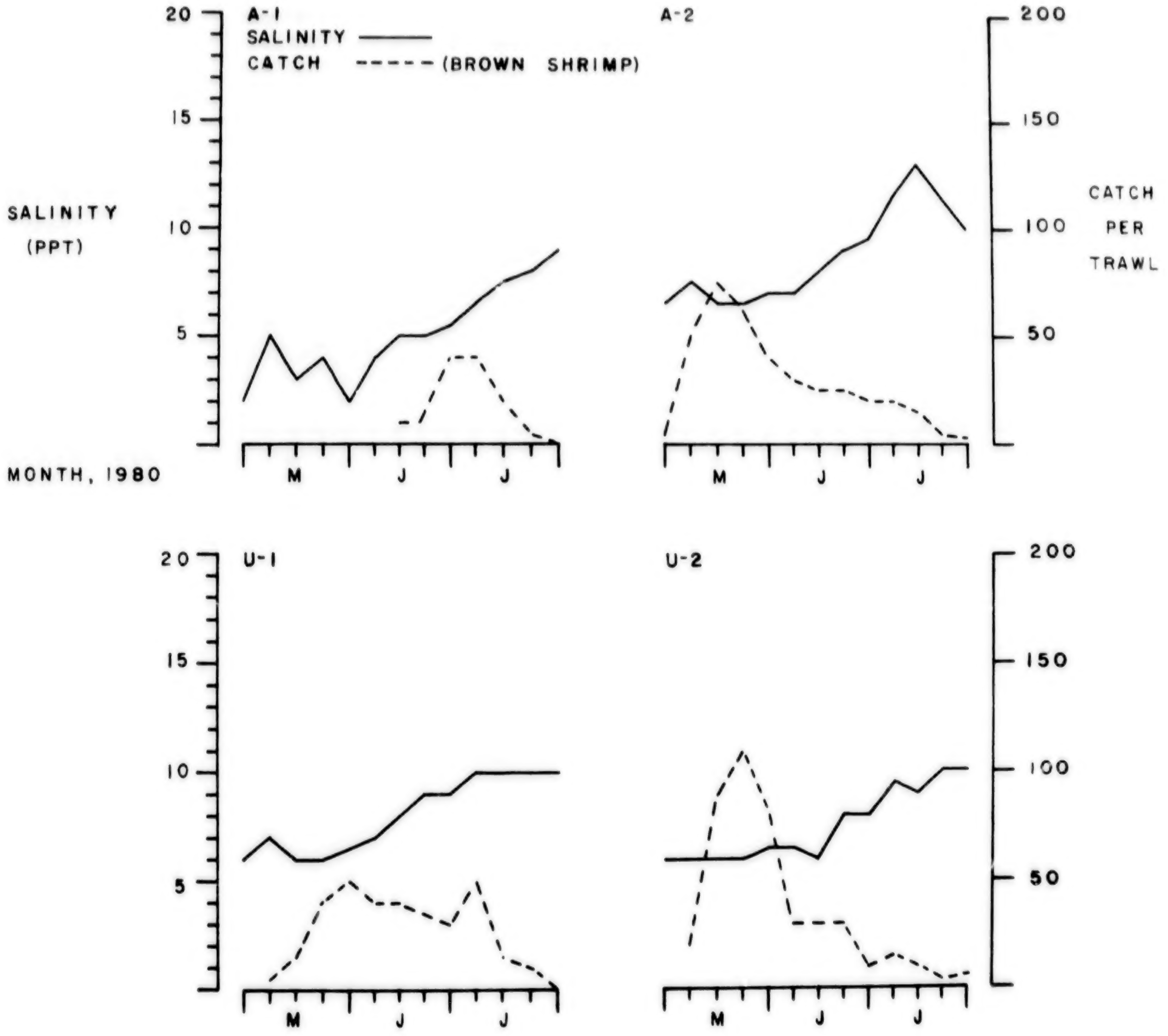

Figure 8. Weekly salinities and catch per trawl of juvenile brown shrimp (Penaeus aztecus) at four locations in 1980.

2. The nursery areas appear to have the capacity to receive a certain amount of "unnatural" drainage and buffer the effects of rainfall on salinity except during periods of extended rain.

3. Extensive drainage into a single nursery area reduces its value as estuarine habitat by reducing average salinities and making it more sensitive to the effects of rainfall within the drainage basin.

4. Relative productivity of estuarine organisms was lower each year in the nursery area with extensive drainage.

5. The data did not show that there were any mass or complete movements of juvenile shrimp from the nursery areas as a response to rapid changes in salinity readings. The most serious effects of drainage into nursery areas appears to be the degree of alteration and the danger that alteration will be severe enough to create an unsuitable habitat during periods of normal rainfall.

RECOMMENDATIONS

The appeal that seafood has for consumers is obvious, judging from the increasing demand for a quality product and the annual rise in dockside and retail prices. It is also obvious that changing uses of lands surrounding the vital nursery areas is inevitable, given the current trends in the value of agricultural and recreational dvelopments. It is important that resource agencies stress the value and fragile nature of these small estuaries and encourage development of adjacent lands to minimize its adverse impacts.

Identification of critical nursery areas must be made and protection of these areas enhanced with proper legislation. Local, state, and Federal agencies should develop joint comprehensive programs which will allow the wisest use of coastal lands and minimize degradation of water quality and wetland habitat. Particular attention should be placed on developing drainage programs which promote (1) strict controls over construction of new drainage systems discharging into critical nursery areas, (2) maintenance of existing ditches and canals during periods of least biological activities in the receiving waters, (3) analysis of the hydrologic and biological impacts of expanding existing drainage systems, (4) development of water management and water control schemes which limit discharge points, and (5) consideration of the cumulative effects of extensive alteration of samll estuaries.

ACKNOWLEDGMENTS

This study was jointly funded by N. C. Sea Grant Program, N. C. Division of Marine Fisheries and N. C. Division of Environmental Management.

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DISCUSSION

Question: What do you think is the mechanism behind reduced productivity in shrimp and freshwater inflow?

Answer: Well that's something that I didn't dwell on because I have no good indication of what stresses are caused by other than these fluctuations in salinity of 3 to 4 ppt in that very short period. We are presently working with some biologist at the North Carolina State University, and some foresters to continue this study and try to evaluate what impacts this has on the available food supply and the metabolic stresses that are created.

ENDANGERED ESTUARINE RECEIVING WATERS: THE EFFECTS OF LOW-FLOW LAND RUNOFF ON HEADWATERS BIOTA

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ABSTRACT

Estuarine receiving waters are often valuable resources for fisheries, recreation, or drinking water supplies. These water resources are commonly threatened by pollution with a wide range of materials from point and diffuse sources. These impacts are often most pronounced at times of lowflow in warm weather due to the high concentrations of nutrients in the land discharges and the absence of subsequent flushing.

Examples of these lowflow impacts on an estuary, the Rhode River, with respect to the nutrients nitrogen and phosphorus are given. The discharges are related to specific subwatersheds and to several different land uses on these subwatersheds. The effects on the water quality of the Rhode River's estuarine headwaters and the potential impact upon a recreational fishery in the estuary are documented.

INTRODUCTION

The Rhode River is a subestuary of Chesapeake Bay, one of the largest estuaries in the world. Chesapeake Bay is located on the Atlantic coast of the United States. One of the most important uses of the bay is recreational and commercial fisheries. The most popular recreational fish in Rhode River are white and yellow perch (Morone Americanus and Perca flavescens, respectively). These two species spend their entire life cycle in the subestuary. In the spring, when water temperatures begin to warm, the adults migrate up the principal freshwater stream which drains most of the Rhode River watershed. They spawn in the freshwater tidal marshes and stream channels and then return to the estuary. In 1976, this spawning occurred in late February and early March. The eggs then hatch and the young fish use the spawning area as a nursery ground for the rest of the summer and early fall. Thus, to maintain their populations, these two species must be able to successfully spawn in the headwaters of the estuary and their progeny must be able to utilize the headwaters as a nursery ground for a major part of the year. Low dissolved oxygen in the headwaters would prevent their survival. Low dissolved oxygen is associated with excessive plankton blooms which are caused by excessive mineral nutrient concentrations in the headwaters of the estuary. The blooms involve both phytoplankton and bacteria. During the day the algae release large amounts of oxygen due to their photosynthetic activity, but at night both algae and bacteria use oxygen in respiratory processes. A diurnal cycle of dissolved oxygen levels results and when the plankton populations become too dense, dissolved oxygen levels reach low levels at night causing suffocation of animal life.

Proper management of this valuable resource (a perch fishery) requires the limitation of nutrient loading from the watershed to a low enough level to ensure fish survival in the estuarine receiving waters. This, in turn, requires a knowledge of the sources of nutrient loading and the temporal distribution of the loading (Correll et. al. 1977; Correll and Dixon 1980).

The example pursued in this article is typical of the fisheries problems encountered in estuaries around the world, although the details are, of course, not generalizable. Many of the world's marine and estuarine fisheries are dependent for their continuance upon headwaters spawning and nursery grounds. These waters are generally more subject to local pollution problems than are the feeding ground of the adult fish.

MATERIALS AND METHODS

DESCRIPTION OF STUDY SITE

The Rhode River is a small (485 ha; 1,212 acres) subestuary of Chesapeake Bay. It is located just south of Annapolis, Maryland. (Latitude 38° 53' North, Longitude 76° 32' West). A map (Figure 1) shows station locations and subwatershed boundaries.

The land runoff data were collected from stations 1, 2, 3, and SL. The land use of subwatersheds is given in Table 1. The area is also given of other subwatersheds which drain directly into the headwaters but were not monitored. The marshes and creek channels near stations 5, 6, 7, and 8 are tidal but remain essentially fresh in the spring when spawning and early larval development occur. The area between stations 8 and 9 is composed of 26 hectares of mud flats and 32 hectares of tidal marshes. It is shallow and functions as a sediment trap for the runoff from the watershed. It also acts as a nursery ground with low salinity (0-10 ppt) and many beds of rooted, submerged aquatic plants. The tidal water volumes, in cubic meters were as follows: Station 6 to 7, 0.2×10^4; Station 7-8, 0.8×10^4; Station 8-9, 14×10^4.

LAND RUNOFF MONITORING

Runoff from watersheds above stations 1, 2, 3 and SL was monitored with 120° sharp-crested Vee-notch weirs. Depth of water upstream of the weirs was monitored in stilling wells and punched in binary digital code on paper tape every 15 minutes with Leupold and Stevens Model 7001 punches. Flow was monitored with Leupold and Stevens Model 61R flow meters equipped with sampling switches. Every 150,000 liters (5,297 ft^3) of flow the switch closed and initiated a water-sampling cycle. A peristaltic pump collected a fixed volume aliquot. All aliquots were composited for one week periods. Every week the volume-integrated samples were collected for analysis of total-P and total-N. At the sample pickup times spot samples were also taken for analysis of nitrate-N, total Kjeldahl-N, dissolved orthophosphate-P, and total-P. Runoff volumes were calculated from the

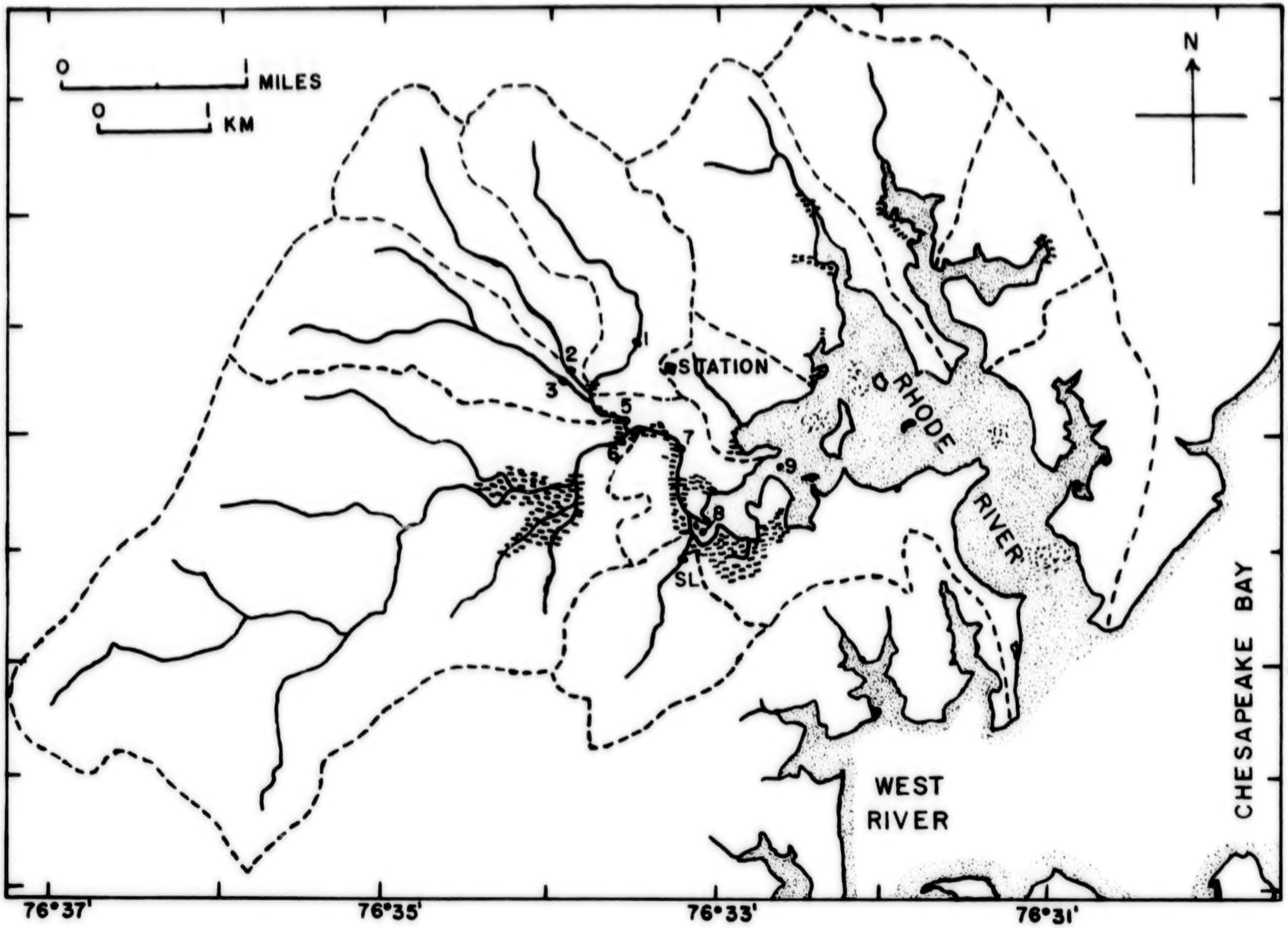

Figure 1. Map of Rhode River estuary and watershed. Data for this article was collected at stations 1, 2, 3 and SL for land runoff and at stations 5, 6, 7, 8 and 9 for tidal water quality. Chlorophyll a data was collected midway between stations 8 and 9.

stilling well depths and the equation: Flow (units^3) = 2.5 (tan 120°/2) (units height)$^{2.5}$. The watershed year was defined as Dec. 1, 1975 to Nov. 30, 1976 and the seasons were arbitrarily defined as three-month portions of that year. Flow-weighted mean nutrient concentrations for stations 1, 2, 3 and SL were used to calculate a flow-weighted mean for the combined four subwatersheds and those values were assumed to be representative of the water quality of runoff from the unmonitored areas. Seasonal mean values for nitrate-N and dissolved orthophosphate-P as percentages of total-N and total-P were calculated from spot sample data. Total-P and the nitrogen parameters were determined as described in Correll et. al. (1977). Dissolved orthophosphate-P was determined after filtration of the water sample through Millipore HA membrane filters (0.45μ pore size). Total volumes of runoff from watersheds above stations 1, 2, 3 and SL were computed for each week of the year and were then multiplied by the ratio of total drainage area to monitored drainage area to obtain total volumes of runoff draining directly into the estuarine headwaters. Sources of nutrients in land runoff were estimated by the use of a linear statistical model relating the size and land use composition of a series of monitored subwatersheds (8 including station 1, 2, 3, and SL in Figure 1) to the total discharge of nutrients from each basin each season (Chirlin and Correll 1977; Correll et. al. 1977).

ESTUARINE WATER QUALITY AND PHYTOPLANKTON

Spot samples were taken weekly at stations 5, 6, 7, 8 and 9 (Figure 1) when weather permitted. These were analyzed for nitrate-N, total Kjeldahl-N, dissolved orthophosphate and total-P using the same techniques described above. Dissolved oxygen and water temperature were measured with a Yellow Springs Instrument Company Model 54, oxygen electrode system. Chlorophyll A was determined by filtering water samples through Millipore HA filters, then using the fluorimetric technique described by Loftus and Carpenter (1971).

RESULTS AND DISCUSSION

NUTRIENTS AND HYDRODYNAMICS

The flow-weighted mean nutrient concentrations of the land runoff flowing into the estuarine headwater receiving area of the Rhode River are shown in Figure 2 (total-P) and Figure 3 (total-N) as weekly bars. Total flow into the receiving waters, as volumes of the tidal waters above station 9 (Figure 1) at mean low water are also shown as weekly shaded bars in Figure 2. It is apparent that most of the flow occurred in the winter, early spring, and mid to late fall. During weeks 23 to 44, flow never exceeded seven tenths of the headwater volume per week and averaged only 0.23. Flow per week was less than 5 percent of the headwaters volume during nine weeks. Total phosphorus concentrations were highest in the summer reaching maxima during weeks 32 (2.4 mg/l) and 36 (1.9 mg/l). Concern for the impact on receiving waters should be expressed when total phosphorus concentrations in receiving waters exceed 200 to 300 μg/l for extended periods in Chesapeake Bay. Due to complexities of estuaries such as mixing rates, flushing, and the

Table 1. Land use data for subwatersheds of Rhode River, which drain directly into the tidal headwaters of the estuary.

Watershed	row crops (ha)	pasture (ha)	forest (ha)	total (ha)
sum of 101, 102,103 and SL	138 (345 ac) (16.8%)	175 (438 ac) (21.3%)	509 (1270 ac) (61.9%)	822 (2055 ac)
121	355 (888 ac)	168 (420 ac)	765 (1910 ac)	1288 (3220 ac)
122	33 (82 ac)	1 (2,5 ac)	266 (665 ac)	300 (750 ac)
Total	526 (1320 ac) (21.8%)	344 (860 ac) (14.3%)	1540 (3850 ac) (63.9%)	2410 (6020 ac)

Table 2. Sources of nutrients by land use categories on the Rhode River watersheds draining directly into the tidal headwaters of the estuary.

Part A. Area yield loading rates for summer, 1976 derived from eight Rhode River basins.

Land Use Category	Total-P (g/ha)	Total-N (g/ha)
Cultivated Crops	130 (0.114 lb/ac)	1290 (1.140 lb/ac)
Pasture	8.1 (0.00714 lb/ac)	240 (0.211 lb/ac)
Forest	31 (0.0273 lb/ac)	-69 (-0.0608 lb/ac)

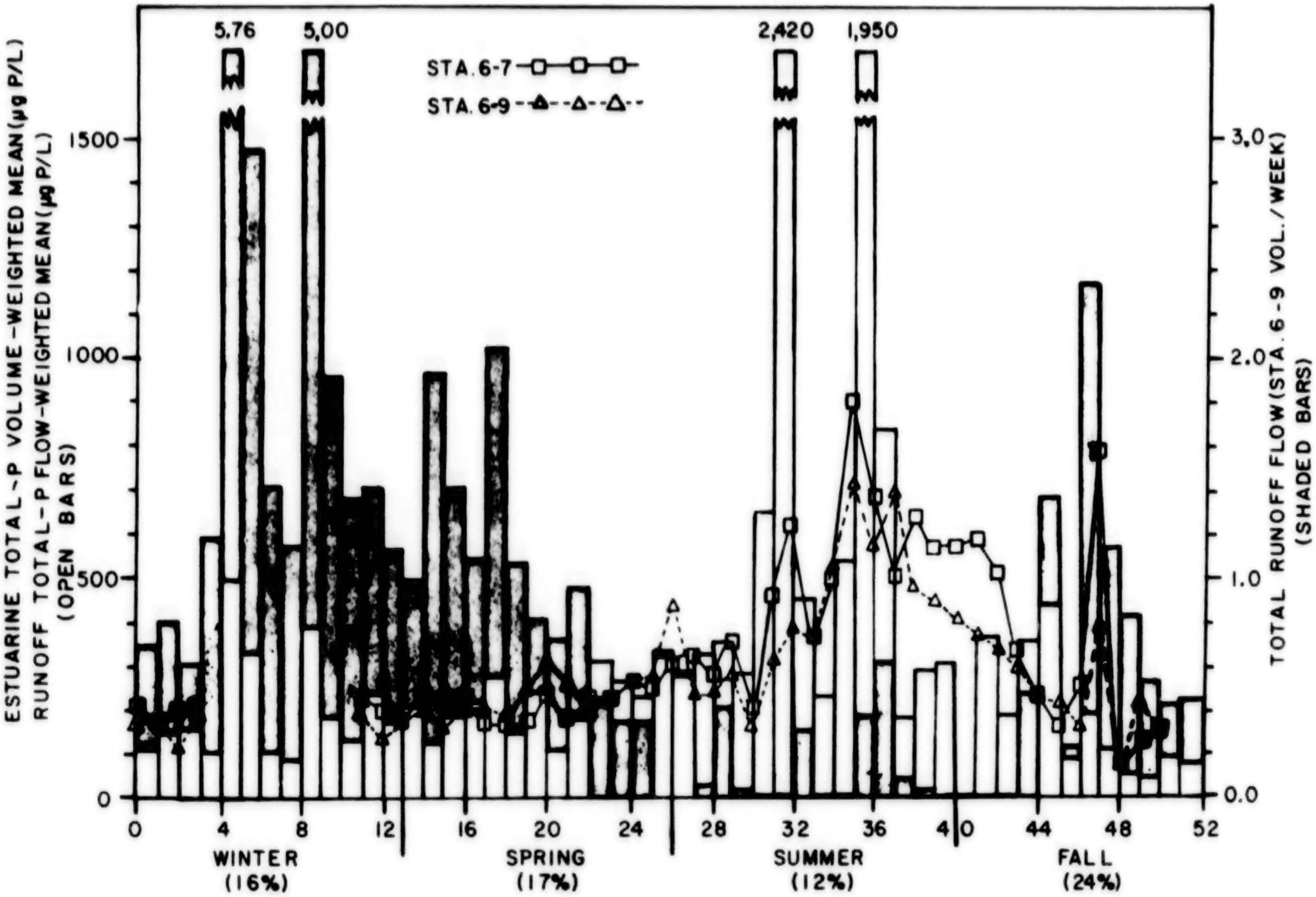

Figure 2. Graph of temporal pattern of phosphorus concentrations and runoff total flows. Open bars are flow-weighted mean total phosphorus concentrations in land runoff waters. Shaded bars are total volumes of land runoff per week normalized to the volume of estuarine water upstream of station 9 in Figure 1 at mean low water. The solid line from point to point is the volume-weighted mean total phosphorus concentrations for estuarine waters between stations 6 and 7. The broken line is the volume-weighted mean total phosphorus concentrations for estuarine waters above station 9. The numbers in parentheses below each season are the mean percentage of phosphorus present in runoff waters as dissolved orthophosphate.

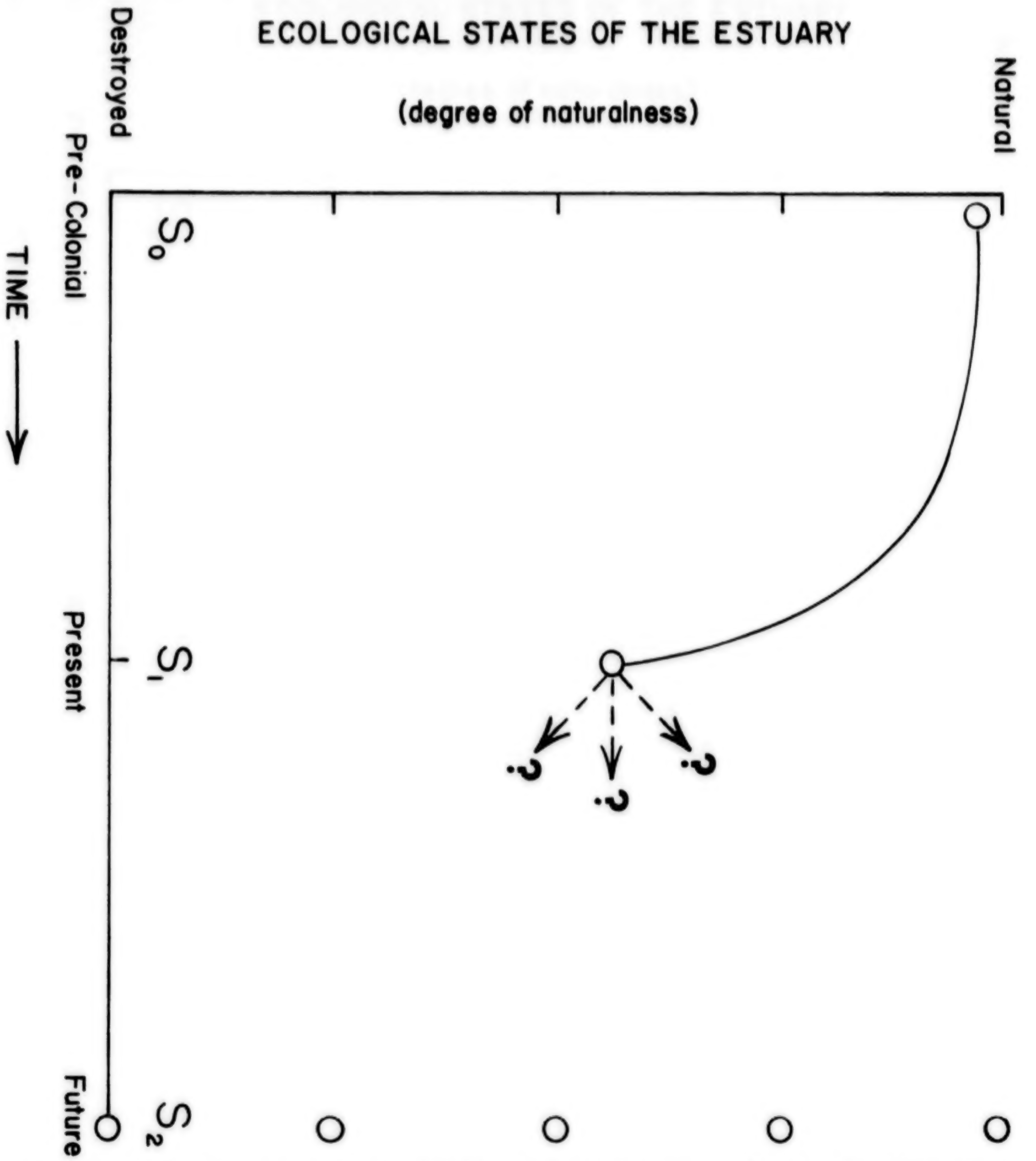

Figure 3. Graph of temporal pattern of nitrogen concentrations. Bars are flow-weighted mean total nitrogrn concentrations in land runoff waters. The numbers in parentheses below the seasons are the seasonal mean percentages of nitrogen in runoff waters persent as nitrate. The solid line from point to point is the volume-weighted mean concentration of total Kjeldahl nitrogen in the estuarine waters between stations 6 and 7 in Figure 1. The broken line is the volume-weighted mean nitrate concentration in the estuarine waters between stations 6 and 7 in Figure 1.

incorporation of phosphorus into bottom sediments, it is best to measure phosphorus concentrations in the estuary. Volume-weighted concentrations of total phosphorus for the waters between stations 6 and 7 and the tidal waters above station 9 are also given in Figure 2. These generally did not reach critical levels for extended periods prior to week 31. They then rose rapidly with peaks of about 600 μ g/l at the end of week 32, about 900 μ g/l at the end of week 35 and about 800 μg/l at the end of week 47. Levels then decline again. All but the last of the total phosphorus peaks are clearly responses to watershed runoff, even though the volumes of runoff are quite low in some cases. For example, the runoff in weeks 31 and 32 had volumes of 0.015 and 0.018 of the receiving waters upstream of station 9 and 1.12 and 1.35 times the volume in the station 6 to 7 area. The phosphorus concentrations in the runoff were 650 and 2,420 μg P/l. The phosphorus concentrations in area 6-7 responded more than those in the entire area upstream of station 9, as expected. The explanation for the peak in week 47 will be presented after other necessary data are discussed. The mean percentages of the phosphorus in runoff waters which was present as dissolved orthophosphate are given for each season (in parentheses on the abscissa).

In Figure 3 the temporal pattern for nitrogen concentrations in runoff is presented. The bars are the flow-weighted mean concentrations of total nitrogen in land runoff. The numbers in parentheses under the seasons are the mean percentages of total nitrogen in land runoff present as nitrate, the form of nitrogen most readily utilized by plankton. It can be readily seen that the levels in runoff seldom exceed the concentrations normally associated with impacts on receiving waters in Chesapeake Bay (2 to 3 mg N/l). Only during weeks 32, 33 and 36 does the level of total nitrogen in runoff exceed 2.0 mg N/l (5.6, 2.5 and 2.8, respectively). The levels of nitrate in the receiving waters are also shown and generally remained very low during the late spring and summer except for a peak in weeks 36 and 37. This is probably due to the fact that runoff waters from the watershed contained only about three times as much nitrogen as phosphorus by weight. Thus, biological uptake which normally occurs in a ratio of about ten nitrogen to one phosphorus draws down the level of available nitrogen (Figure 3) but leaves excessive levels of phosphorus (Figure 2) during the summer. Total nitrogen in the receiving waters (Figure 3) was near or above 2 mg N/l only from week 38 to 42 with a peak of 4.2 mg N/l at the end of week 42. At that time an unusually high ratio of nitrogen to phosphorus (8.5) was present at the same time that nutrient levels were far above acceptable standards. The results will be discussed in the next section.

ESTUARINE RECEIVING WATERS IMPACT

Water temperature and dissolved oxygen levels at station 7 are plotted in Figure 4. In the winter and early spring dissolved oxygen levels remained high. This included the spawning period (weeks 11-15). During weeks 20 and 21 the dissolved oxygen went down to between 6 and 7 mg/l and the water temperature increased to 10. Then temperature and dissolved oxygen

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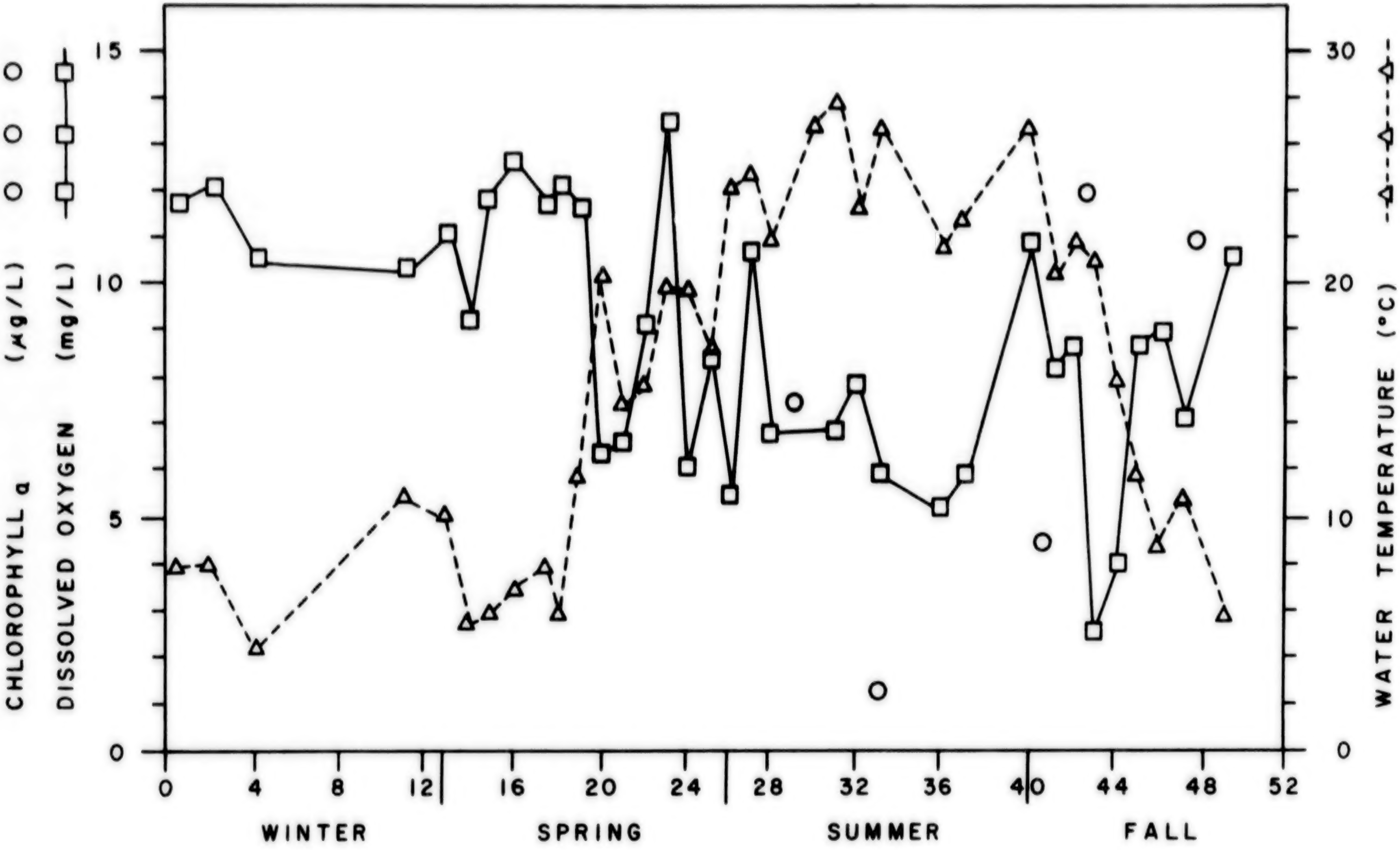

Figure 4. Graph of daytime water temperature and dissolved oxygen levels at station 7 and of Chlorophyll a levels in the phytoplankton, midway between station 8 and 9.

fluctuated until week 28. After week 28, water temperature remained high (over 22° C) and dissolved oxygen remained low (5-8 mg/l) until week 40, when dissolved oxygen increased for two weeks. Beginning in week 43, a cooling trend is evident and water temperatures dropped steadily to 3°C by week 49. Dissolved oxygen dropped to an observed low for the year of 2.7 mg/l (at 9:10 a.m.) in week 43, remained low for a week, then recovered. Chlorophyll a levels in phytoplankton were also measured as an index of response at the first trophic level. These values also reached a maximum during week 43. The high plankton levels and low dissolved oxygen during weeks 43 and 44 are the most probable explanation of the high phosphorus levels at stations 6 and 7 in week 47. When estuarine waters go anaerobic, even briefly overnight, high levels of phosphate are released from bottom sediments. Our lack of more than weekly data points and the fact that the dissolved oxygen readings were made several hours after sunrise made this conclusion tentative. However, sufficient runoff occurred (Figure 2) during week 47 to flush the area, and the runoff contained a flow-weighted mean concentration of phosphorus of 190 μg P/l while the estuarine waters between stations 6 and 7 at the end of week 47 had 780 μg P/l (Figure 2). In the case of total nitrogen, this discrepancy is present but not as large in week 47. Runoff waters had a flow-weighted mean concentration of 760 μg N/l while estuarine water had 1280 μg N/l (Figure 3).

Let us look at the sequence of events which occurred in late summer and fall. During weeks 36 and 37 runoff volumes (Figure 2) which summed up to the volume of the headwater estuarine area were discharged from the watershed. They contained very high phosphorus levels (Figure 3) and prolonged high total phosphorus (Figure 2) and total nitrogen levels (Figure 3) due to very low flow conditions (Figure 2) through week 43. During this period estuarine nitrogen to phosphorus ratios also reached 8-9 and a phytoplankton bloom developed (Figure 4). Water temperatures were still high and dissolved oxygen exhibited strong diurnal cycles, resulting in very low oxygen levels in the mornings during weeks 43 and 44. The receiving waters must have gone anaerobic sometime within the next several weeks and the result was the release of nutrients stored in the sediments during week 47. This anaerobic period probably occurred during week 47 but went undetected. Only the occurrence of high stream flows (Figure 2) and cool weather (Figure 4) prevented this plankton activity-nutrient release cycle from becoming self-reinforcing and the occurrence of widespread damage to many species of biota.

SOURCES OF THE NUTRIENTS

With the proper data base the sources of nutrients can be estimated for an entire year, a season, or a particular storm event. In this case we are most concerned with the sources of nutrients in the storm events of weeks 36 and 37 (Figures 2 and 3). In order to estimate these sources, the first step was to calculate area-yield loading rates during the summer of 1976 with a statistical model. These are given in Table 2, part A. Cultivated cropland had the highest rates for nitrogen and phosphorus by far. The estimated ratio of yield rates for nitrogen and phosphorus was also close to ten. Forest phosphorus

Part B. Calculation of the sources of nutrients from water shed land use data (Table 1) and area uelds (Table 2, Part A).

	Crops	+ Pasture	+ Forest	= Total
P-equation:	526(130)	+ 344(8.1)	+ 1540 (31)	= 118.9 kg P
	68.4 Kg P	2.79 Kg P	47.7 Kg P	(262 lb)
	(57.5%)	(2.3%)	(40.1%)	
N-equation:	526 (1290)	+ 344 (240)	+ 1540 (-69)	= 656 kg N
	679 Kg N	82.6 Kg N	106 Kg N	(1440 lb)
	(104%)	(12.6%)	(-16.2%)	

area yield was 24 percent that of cultivated crops and pasture was only 6 percent that of cropland. For nitrogen area yield, pasture was 19 percent that of cropland, while forest had a negative yield. This indicates forest took up more nitrogen from waters draining through it than it released. This is probably due to the high rates of evapotranspiration in Maryland forests during the summer. It is not unusual in the summer to see small streams flowing from areas of cropland and pasture into forests, then drying up before emerging again.

The next step in calculating the sources of nutrients in the runoff events of weeks 36 and 37 is the calculation of the estimated summer season's total area yields of phosphorus and nitrogen from the watersheds of the Rhode River estuary, which drain directly into the headwaters of the estuary. The area of each land use is given in Table 1. In Table 2, part B, the total nutrient yield in runoff is calculated as the sum of cropland, pasture, and forest components. Each component is the product of the number of hectares of that land use and the area yield for the summer of 1976. Finally, the percent of the total seasonal nutrient contributed by each land use category was calculated. Thus, the phosphorus loadings during weeks 36 and 37 were estimated to have originated 57.5 percent from cropland, 2.3 percent from pasture, and 40.1 percent from forest. The nitrogen loadings were estimated to have originated 104 percent from cropland, 12.6 percent from pasture, while 16.2 percent of the loading was removed in the forest.

This information is specific for the summer of 1976 and the conclusions probably would be quite different for other time periods. This information could lead to improved management of the watershed to reduce the likelihood of damage to the fisheries of the estuary. One reasonable strategy would be to attempt to reduce the nitrogen in summer runoff from cropland. The results would be a reduction in the nitrogen to phosphorus ratio in runoff entering the estuary and a consequent reduction in plankton growth. The reduction in nitrogen runoff from cropland might be accomplished by alteration of crop fertilization and tillage practices or by preservation and enlargement of freshwater swamps and marshes along the drainage channels. These swampy areas are very effective denitrifiers. In this particular case the problem period is in the month of August. The primary crops cultivated are corn and tobacco, which have begun to mature and senesce by that time. They are, therefore, less likely to be removing available, soluble nutrient forms from the soil and have probably begun to leach significant amounts of nitrogen from their leaves. This could account for the fact that the nitrogen to phosphorus ratio in the runoff was relatively high, for the Maryland coastal plain.

CONCLUSIONS

An annual cycle of data on land runoff, estuarine receiving water quality and biological impact has been presented and analyzed with respect to a specific estuarine fisheries problem: the spawning and nursery ground activities of two popular recreational fish species. The volumes and nutrient composition of land runoff have been related to estuarine water quality. A period of depressed dissolved oxygen in the estuary has been related to high plankton activity, which was induced by storm runoff during two weeks in the summer preceeded and followed by periods of low flow and, therefore, of low flushing rates. The nitrogen to phosphorus ratio in this runoff as well as the concentration of nutrients were favorable to high plankton growth rates resulting in low dissolved oxygen at night which, in turn, triggered further nutrient releases from estuarine bottom sediments. The nutrient discharges from eight basins in the summer season were used to calculate area yield loading rates from three different land use categories which are common on the watershed. The land use composition and areas of the watersheds which drain directly into the estuarine headwaters and the area yield rates were then used to estimate the sources of the nutrients in the runoff events which triggered the adverse responses found in the estuary. The majority of the nutrients came from cropland rather than pasture or forest although cropland accounted for only 32 percent of the watershed area.

ACKNOWLEDGEMENTS

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CHAPTER 15

FRESHWATER INFLOW PLANNING: PART 2

STRATEGIES FOR THE MANAGEMENT OF ESTUARIES

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ABSTRACT

Ideally, estuarine management is the central element in the man-nature structure, positioned between information inputs and decision processes, on the one hand, and action arenas and system states, on the other. Tools of estuarine management include various forms of zoning, permitting authority, and lease/purchase. Each of these may be applied effectively in the upstream or the local context. The best goal in estuarine management is the predisturbance state, and to achieve this goal both general and site-specific knowledge are required. At present no estuary of our Nation is being properly managed, and none has an adequate management structure. Although some progress in estuarine management can be made under existing authorities, major impetus will come only through directed Federal action.

INTRODUCTION

The natural waters of the earth have contributed immeasureably to the development and support of civilization, but the story of society's historical abuse of aquatic environments is well known. This is true of estuaries of the United States, in particular. Documentation may be found in the National Estuarine Inventory of the U.S. Fish & Wildlife Service (1970) and in a hundred or more recent technical articles and reports. Efforts are now being made to reverse this trend, but suddenly we face the question of how can estuaries really be managed. By what institutional mechanisms and by what physical means can society accomplish the necessary management tasks, especially in the face of the various competing and often conflicting interests? In order to answer these questions we first must understand the structure of estuarine management, not as it is but as it must become if estuaries are to be properly managed. To accomplish this we will develop a conceptual model of an appropriate estuarine management system.

THE STRUCTURE OF ESTUARINE MANAGEMENT

In Figure 1 are shown three ecological states of the estuary in terms of degree of naturalness, the pre-colonial, present, and alternative future states. These are referred to respectively as S_0, S_1, and S_2. For most of our estuaries we do not know precisely what S_0 was like because they were not studied thoroughly before we modified them and, in any event, the aborigines certainly had some influence. However, we do know roughly what S_0

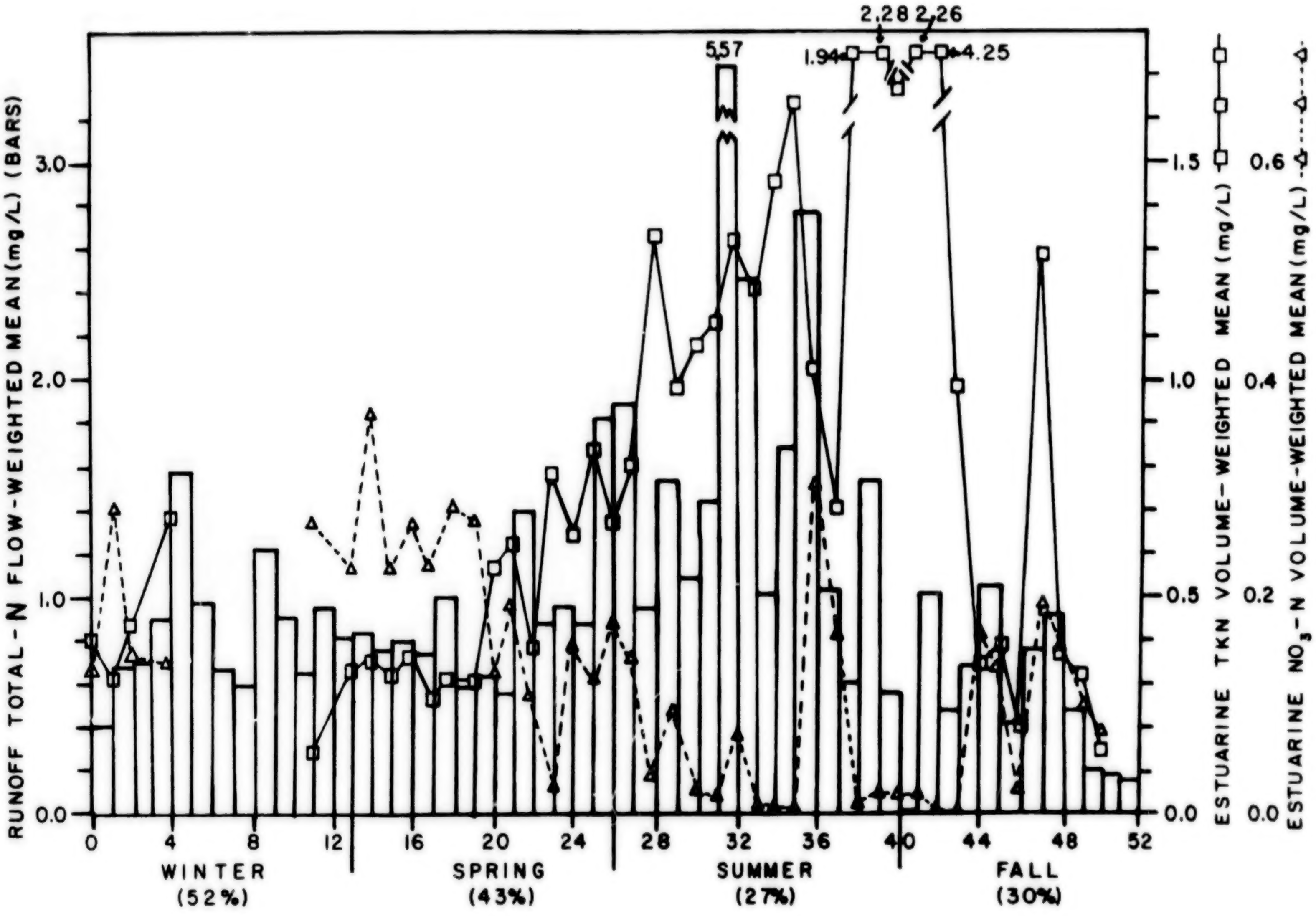

Figure 1. Environmental states of the estuary in relation to historical time.

must have been like for most of the estuaries, and this knowledge is quite valuable as a reference point if we wish to restore them. The manager's task really begins with the present state (S_1). He must aid in defining which of the potential future states should be achieved, and then he must bring to bear the resources necessary to achieve the desired S_2.

In Figure 2 we see the arenas for managerial action. At the manager's disposal are the tools of regulation and intervention, and each of these may be employed in the upstream basin or in the local estuarine environment. In the present context the word "regulation" is used in the sense of controlling or limiting the actions of others. For the most part, this is passive management because it largely involves acceptance or denial of requests for permits to modify the environment. "Intervention," on the other hand, entails positive action or intercession on behalf of the estuary and its inhabitants. Regulation might involve refusal of a permit to build an upstream dam. Intervention might entail making the dam operators open the gates and permit downstream flow as dictated by salinity conditions in the estuary. In order to move the estuary from $State_1$ to the desired $State_2$, the estuarine manager has at his disposal a bundle of mechanisms which can be grouped under the four management arenas. However, most efforts at estuarine management in the past have involved regulation rather than intervention, and most regulation has been limited to the local rather than the upstream arena.

In the conduct of its duties management must also interface with a variety of outside interests and information sources to determine which of the potential future states should be achieved and how best to muster available resources to achieve the desired state (Figure 3). Policy decisions should be made with the invited participation of the public, private interest groups, and other management agencies. Shorter term operational decisions must be made within the general policy framework, and these depend upon intimate technical knowledge of the system being managed. Important here are research, modeling and simulation, and input of data from system monitoring.

In overview (Figure 4), estuarine management is the central element in the whole man-nature structure, positioned between information inputs and decision processes, on the one hand, and action arenas and system states, on the other. Management is the translator and action generator of the system.

TOOLS OF ESTUARINE MANAGEMENT

From the foregoing we can now recognize four areas in which management can influence the future state of the estuary (Figure 5). Although it must implement the goals and policies established through decision processes, management is in a strong position itself to influence these goals and policies. Nor is management simply the handmaiden of science and technology. It must determine what research and monitoring is to be carried out to provide the most sophisticated and meaningful knowledge base for its own anticipated actions.

Estuarine management has or should have authority to regulate and intervene in activities throughout the drainage basin. Some of the types of action in the management

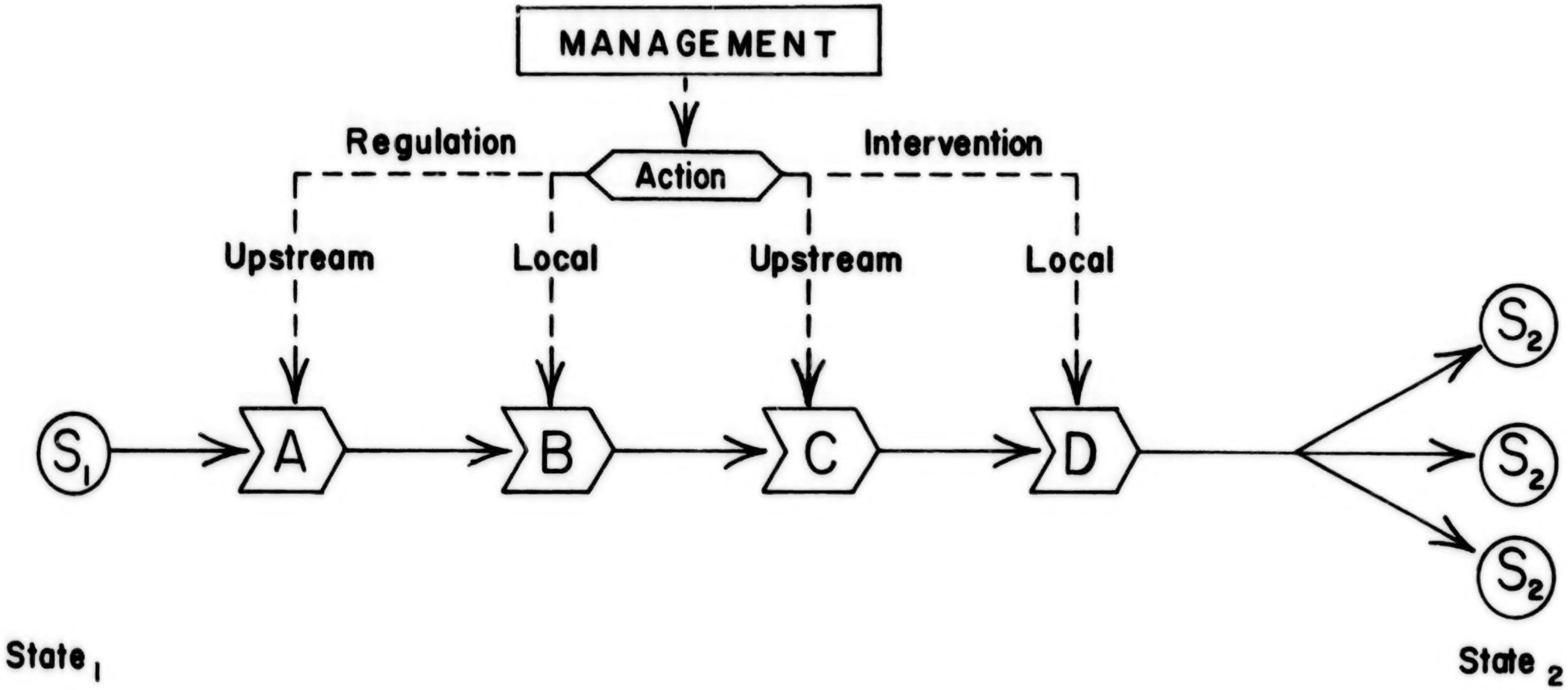

Figure 2. The four arenas for estuarine management action.

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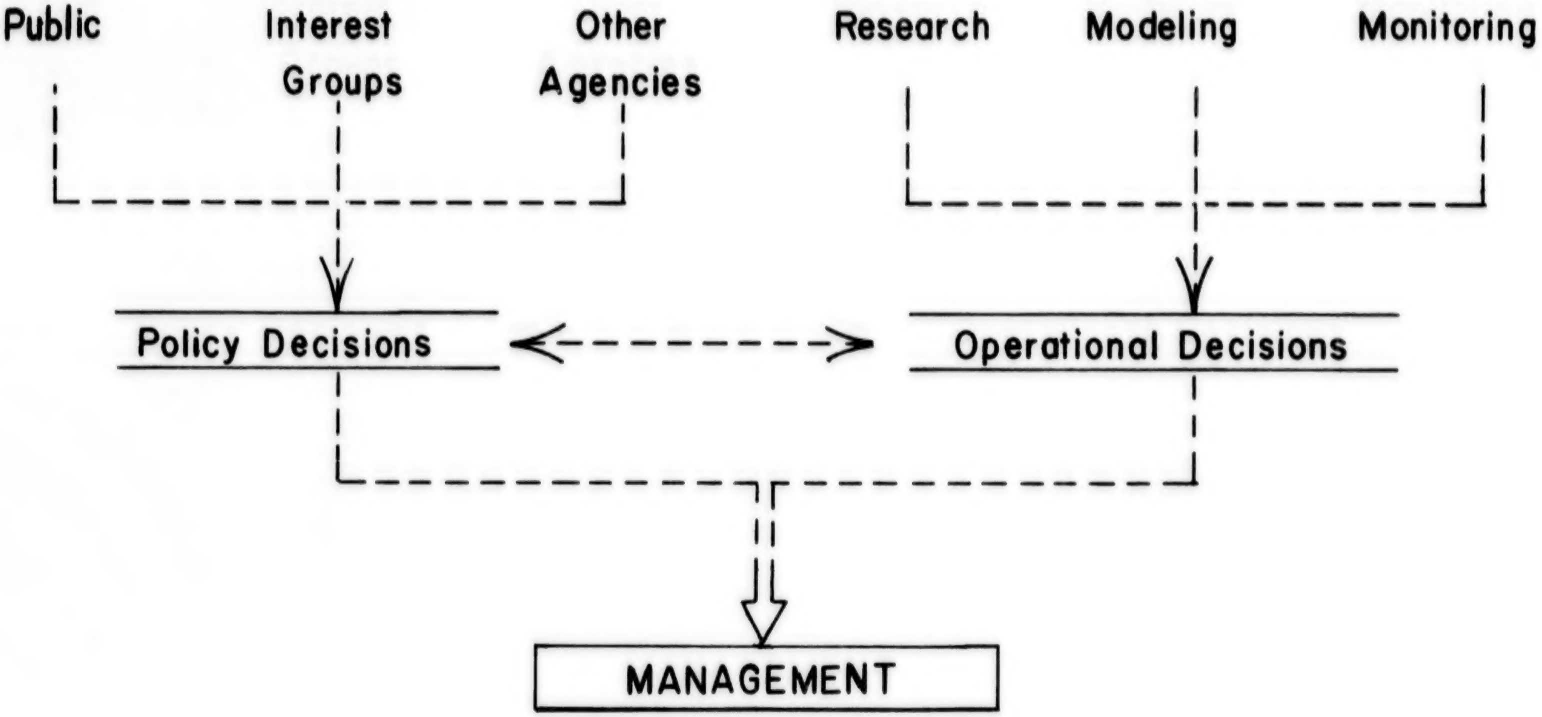

Figure 3. Inputs to the decision making processes and to management.

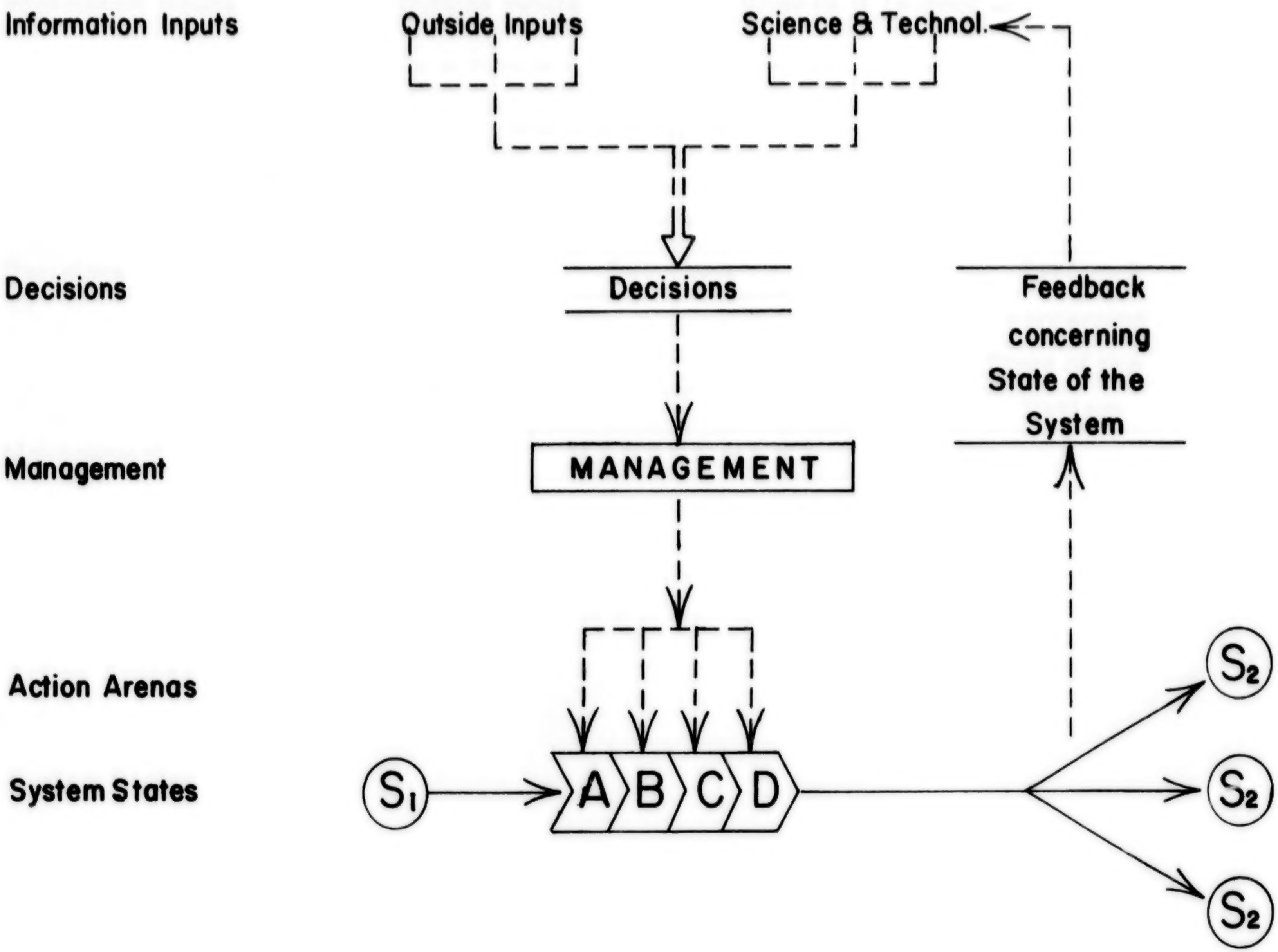

Figure 4. A conceptual model of the total structure of estuarine management and its relation to the system being managed.

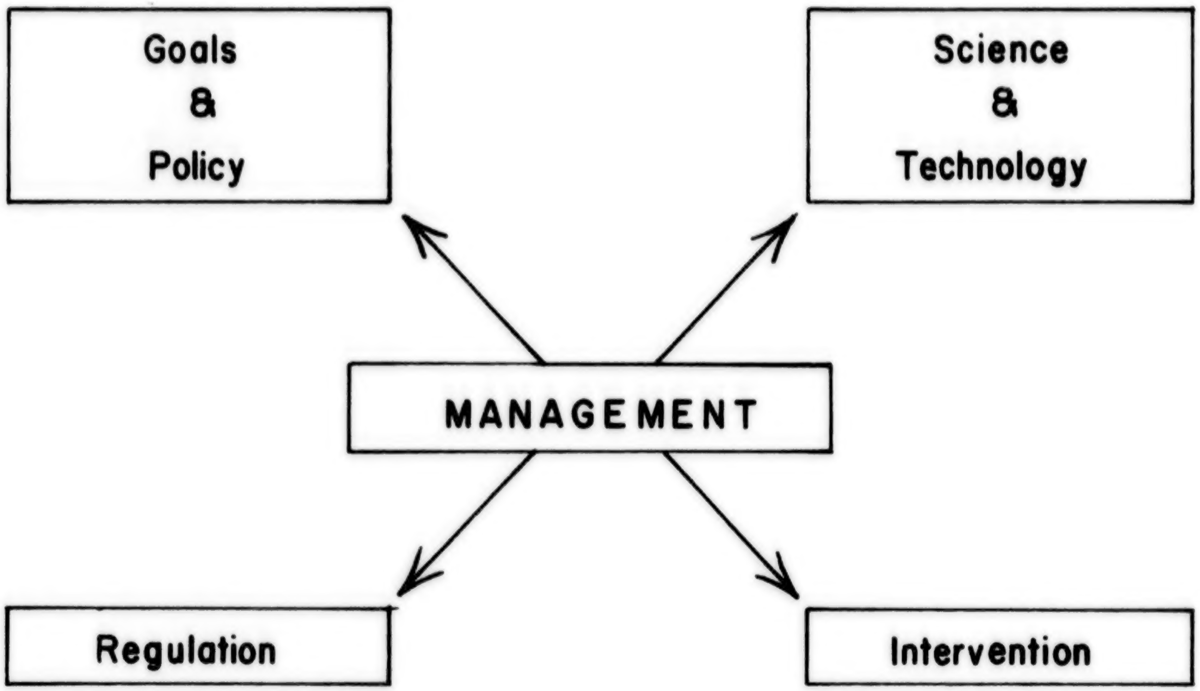

Figure 5. Areas through which management may influence the future state of the estuary.

arenas are spelled out in Table 1. Here we see upstream regulation of activities within the stream, on the floodplain, and in uplands of the surrounding basin. Locally, regulation might take place within the estuary, in related wetlands and lowlands, and on the barrier islands and beaches. The influence of most of the regulated activities on freshwater inflow to estuaries has been discussed in detail by Darnell et al. (1976) and need not be reiterated here.

Of special interest, however, are opportunities for active intervention, because most of these have not received comprehensive treatment. A few examples are illustrative. (1) It seems possible that freshwater storage structures might be developed for the specific purpose of supplying fresh water when needed by the estuary. For example, in coastal Louisiana the nearly fresh Lake Maurepas might be dammed and leveed and used as a freshwater holding tank for Lake Pontchartrain. (2) Diversions might be developed between alternate freshwater sources and estuaries to optimize the distribution of fresh water. For example, to let fresh water flow from the Mississippi River into Lake Pontchartrain, it could be diverted through the Industrial Canal or the Bonnet Carre' Spillway which already exist, or a new cut could be made at the site of an upstream bayou, thereby providing three positive mechanisms for introducing fresh water from the river into the lake. (3) Another mechanism for supplying fresh water to the estuary when needed might derive from the permitting authority. Upstream water diversion permits might be approved with rescission clauses, i.e., stipulations, which prohibit diversions during periods when the freshwater flow should be shunted to the estuary. (4) Storage of fresh or low salinity water by estuarine-related marshes and swamps could be enhanced by increasing the depth or areal extent of such wetlands. Many opportunities for innovative active intervention do exist. They should be explored and then developed, as necessary.

What legal tools are available to aid in estuarine management? These fall into three categories as given below:

ZONING. Local and regional zoning ordinances could be employed to protect valuable wetlands, floodplains, and critical watershed environments. Such ordinances have been widely used for protection of land areas, but they could be used for protection and enhancement of aquatic systems, as well. Sanctuary designation, for example, is a form of zoning. Where appropriate zoning ordinances exist they should be implemented. Where they do not exist efforts must be made to achieve their passage.

PERMITTING AUTHORITY. One of the most powerful sets of tools derives from the regulatory ability stemming from the permitting authority. Nonconforming permits could be denied. On the other hand, some permits might be approved subject to certain conditions such as least damaging technology or rescission clauses (as noted above). This area also lends itself to bargaining and development of mitigation measures.

LEASE AND PURCHASE. Outright purchase, with or without condemnation proceedings, is always a possibility for critical environmental sites. However, long-term leasing of certain rights might accomplish many of the same ends with much less cost and social trauma.

Table 1. Examples of management action in the four estuarine management arenas.

I. REGULATION OF HUMAN ACTIVITIES

A. Upstream

1. Regulation of instream construction
   (dams, cut-offs, channels, etc.)
2. Regulation of floodplain activities
   (destruction of floodplain vetetation, construction of levees, canals, and other flow-modification features)
3. Regulation of activities in the surrounding basin
   (wells and other water table lowering structiues; canals and other water diversion devices; pavements, culverts, and other rapid run-off features)

B. Local

1. Regulation of in-water activities
   (dredge and shoal activities; construction of bridges, piers, baffles, barriers, and other flow-modification structures inside the estuary or at the passes)
2. Regulation of nearby wetland and lowland activities
   (construction of canals, levees, and landfills; destruction of vegetation in marshes, swamps, and other coastal lowlands)
3. Regulation of activities on barrier islands and beaches
   (construction of cuts and canals; destruction of vegetation and high dunes; water table lowering)

II. INTERVENTION

A. Upstream

1. Development of upstream freshwater storage structures
2. Water release from upstream impoundments.
3. Addition of rescission clauses to upstream water diversion permits

B. Downstream

1. Development of local freshwater storage structures
2. Development of alternative freshwater sources
3. Restoration of coastal wetland habitat

Just as active intervention is an area which is yet to be fully exploited, the realm of legal tools has yet to be thoroughly explored and tested. The recent article of Dedmon (1980) indicates some of these possibilities.

GOALS OF ESTUARINE MANAGEMENT

The goals of estuarine management must consist of some compromise between the requirements for ecosystem health and the expressed desires of interest groups and the public. Specific conditions of ecosystem health will have to be defined for each estuary, but a firm general working definition has recently been proposed (Darnell and Soniat 1981). This is given as follows:

"Ecosystem health is that state in which the components and processes remain well within specified limits of system integrity selected to insure that there is no diminution in the capacity of the system to render its basic services to society throughout the indefinite future."

As pointed out by the authors, three factors underlie this definition:

(1) Dedication to the proposition, espoused in the National Environmental Policy Act of 1969 (NEPA), that unborn generations shall not inherit a ravaged biosphere;

(2) Existence of a knowledge base sufficient for the determination of critical limits of tolerance; and

(3) Willingness of society to establish limits of human intrusion well short of the absolute limits of system tolerance, i.e., willingness to maintain a significant margin of safety."

Do we have the knowledge base for the management of estuarine systems? In a general sense we do. In Figure 6 we see that the typical estuary is inhabited by four classes of organisms. Residents include those requiring waters of low salinity, those requiring high salinity, and those which require intermediate salinity or which exhibit fairly broad ranges of salinity tolerance. Superimposed upon the three resident classes is a group of marine-derived highly migratory species which require a variety of different salinities and habitats in order to complete the different life history stages. These migrators also depend upon appropriate currents and flow rates at specific seasons. Among the migrators are most of the commercially important species. To provide for the needs of both residents and migrators, it is essential that salinity conditions of the estuary be variable in both space and time and that flow rates of the water currents not be materially altered from those naturally prevailing. The best goal for management of any estuary is to let nature be the primary guide. S_2 should approximate S_0 in certain essential ways.

PUTTING IT ALL TOGETHER

We have examined the structure of estuarine management and determined that there are four basic areas of opportunity for management to influence the future state of the estuary: long range policy, science and technology, regulation, and intervention. We have examined the tools of estuarine management including aspects of the above as well as the three categories of legal action available: zoning, permitting authority, and lease and purchase.

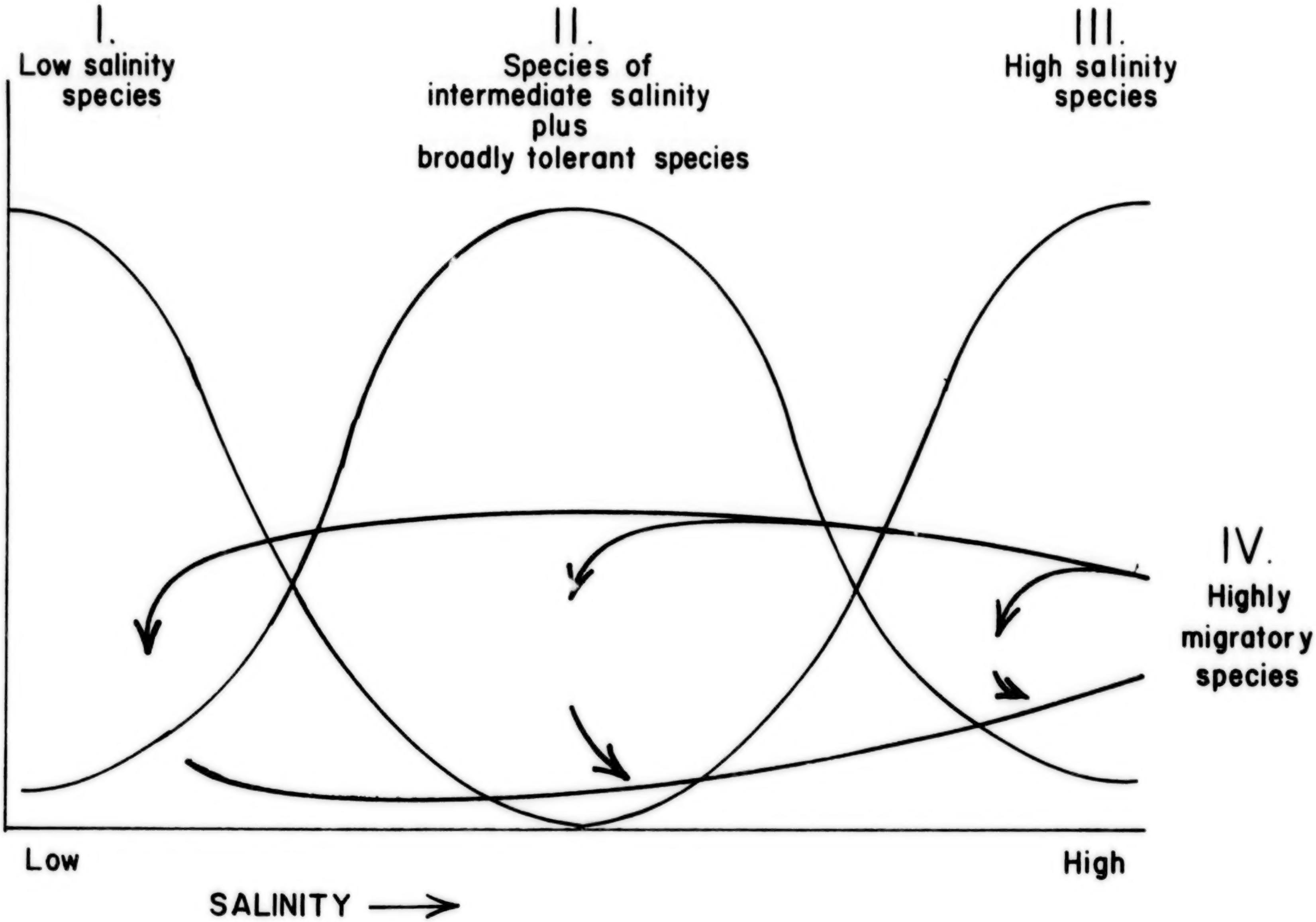

Figure 6. Salinity characteristics of species groups which inhabit the typical estuary.

We have also focused briefly upon the goals of estuarine management, defining ecosystem health, identifying the four basic classes of estuarine inhabitants, and emphasizing the importance of letting the natural system be the guide for management. How does this exercise in concepts relate to the real world?

Right now we are a long way from achieving proper estuarine management. In the first place, who is the estuarine manager? Nowhere in the Nation can we identify a legally constituted agency with unambiguous authority to carry out the effective management of a single estuary. Partial precedents do exist in such agencies as the Tennessee Valley Authority, Pacific Northwest Basin Commission, and Bay Conservation and Development Council (for San Francisco Bay). What we do have is a variety of Federal, state, and local agencies with overlapping and often conflicting authorities, each attempting to manage a different aspect of the estuary. Seldom is there a master plan, and seldom is there authority to influence or control upstream activities which may have dramatic effects on the estuary.

In the second place, we do not have the full array of necessary legal tools available to those agencies which do have some estuarine jurisdiction. Most of our laws stop at the water's edge. In our western states historical water removal rights have often been considered inviolable, regardless of downstream effects. An especially thorny issue stems from the fact that streams cross political boundaries, and upstream states have little vested interest in estuarine management.

Thirdly, we do not have all the site-specific information we need for management of individual estuaries, and it is the site-specific knowledge that is going to make the difference because each estuary and each watershed has a "personality" all its own. A managerial strategy which works for one estuary may be totally inappropriate for another. This is a critical point which must be grasped by agencies attempting to manage estuaries.

Despite the considerations outlined above, there is room for some optimism. We have come a long way just to be able to factor the problem into its components, put the pieces back together in meaningful fashion, and then look at the whole problem in an organized way. We can now at least conceptualize management structure as it should be and show pathways toward solutions. Because many of the solutions involve interstate and regional considerations, there must be strong Federal involvement. The Federal Government, of course, is already heavily involved in estuarine deterioration through such programs as Sea Grant and Coastal Zone Management, to name only two. Despite legislative intent and perhaps not faulting any particular group, there has not been anything like a balance between exploitation and environmental protection.

In our search for solutions it seems that what we really need most is an Executive Order from the White House pointing out the values of the Nation's estuaries and directing all Federal agencies to give detailed consideration to protection of the living resource base. This should be followed by specific Federal and state legislation empowering the agencies to protect the estuarine environment and including some authority to influence activities upstream. Whether a given estuary should be managed by a specific commission or whether it might continue to be managed by a series of different agencies, each with partial jurisdiction, cannot be decided here. Experience must dictate the management structure which works best in each instance. However, regardless of which way we go, for each estuary there must be developed a specific management plan, and the actions of each agency must be weighed within the framework of the accepted plan.

Until the day when estuaries are rescued through bold Federal action, we must seek more effective ways to manage with the tools already available. One of these tools certainly has not been exploited to its fullest, and this may be laid at the doorstep of the U.S. Environmental Protection Agency. All major upstream activities likely to affect the quality of the environment in a significant way must be preceded by an environmental impact statement if there is Federal involvement. This statement should not only address the local environmental effects, but in light of the present discussion, it should address downstream effects upon the estuary, as well. Strict attention to this requirement should greatly retard the rate of estuarine deterioration because most of the major upstream activities involve Federal funding. Another matter, also in the lap of the Environmental Protection Agency, deals with the problem of cumulative impact. The Nations's aquatic resources are being impacted not only by the major federally funded projects, but they are also being "nickeled and dimed to death" by hundreds of smaller local activities whose cumulative effect can be severe (Darnell 1978). Comparison of S_0 and S_1 for individual estuaries reveals the magnitude of this issue which has not been faced squarely by management agencies to date. Perhaps ways may be found for citizens' organizations to insist upon agency compliance with legislative intent.

Estuarine management is complex, but it is not an intractable problem. Partial solutions already exist, and others are within grasp. However, the major impetus will come when the Federal Government decides that the coast is really worth saving and focuses upon the heart of the problem which is the estuary.

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A DYNAMIC METHODOLOGY FOR CHARACTERIZING AND MONITORING ESTUARINE ECOSYSTEMS

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INTRODUCTION

The subject that gives rise to this symposium has long been of interest to researchers and resource managers. In 1970, the National Academy of Sciences and Engineering in its report on the Wastes Management Concepts for the Coastal Zone pointed out that freshwater inflow should be considered as an urgent and specific problem: "As industrial operations, river storage, and diversions increase, advance predictions of the principal effects of increasing or decreasing freshwater flow, or of modifying the seasonal flow patterns, will become essential" (National Academy of Sciences/National Academy of Engineering 1970).

This need that the Academy saw some ten years ago still exists and, therefore, this symposium has been convened with the expressed goal of formulating recommendations for solution of the many problems associated with freshwater inflow to estuaries. Of these problems, those of a scientific and technical nature are of special significance in that, hopefully, these solutions will serve as the basis for the planning and management decisions. Also, these scientific and technical problems are special in that they demand a level of accuracy that is not generally utilized, nor possibly permitted, in management or planning activities. Scientific-technical problems require greater precision and reproducibility because of the demands of the protocol that must be followed in applying the classical scientific method to a problem. They are broad problems requiring a separate approach for their solution. Because of these and other differences, they are worthy of separate consideration, and are in fact being given that separate consideration in other sessions of this symposium. They are not the main concern in this paper, but are considered in respect to their influence upon management-planning activities which consist primarily of taking existing scientific information and "translating" it into a usable form. In this sense, usable means that it will meet the demands of the protocol required in the "art of the possible" (e.g., the political process)

Through numerous "baseline" studies, monitoring studies, and environmental impact studies there has been developed a wealth of data relating to the estuarine areas of the United States. When questions relating to planning and management arise, decisionmakers and/or their advisors have expectations of receiving at least qualified, if not definitive, answers from these information sources. Their expectations are not always fulfilled. This deficiency is recognized and attempts to correct it are being made. An example of one such attempt is the coastal Ecosystems Characterization Program being conducted by the U.S. Fish and Wildlife Service, a program expected to produce "Efficient ways to manage and to transfer the large mass of information to decisionmakers," (U.S. Fish & Wildlife Service 1979). The methodology described in this paper pursues that theme.

In the development of such procedures and alternatives, a management information and transfer system that consists of brief statements of principles is likely to receive greater use than long narratives. Such principles should be used as standards against which specific cases could be gauged in much the same manner that a physician compares an individual's pulse rate, blood pressure, and other vital descriptors against those that have been recorded in his past examinations. With these individual historical data comparisions, along with comparisons against other "normal" population standards, one is able to determine if an individual is within the "healthy" range for his given age, height, weight, sex, etc. It is the intent of this paper to present an approach that applies principles which are similar to this medical analogy to estuarine ecosystems.

The proposed approach involves consideration of the large collections of information that have come from disparate sources, with the objective of discovering its weaknesses, pointing out its predictive value, and appraising its range of application. This method is proposed with the full understanding that there are potential flaws because the data may not be sufficiently synoptic, may not be the epitome of classical statistics, or may not have the scientific purity of a laboratory experiment. Even so, patterns and trends should exist that are of value for comparative purposes and from which predictions can be made or inferences drawn. Therefore, a methodology is proposed that utilizes extant data, from disparate sources, for purposes of determining or predicting transitory and/or permanent effects that natural and/or man-made changes (i.e., alteration of freshwater inflow) will cause in an estuarine ecosystem.

MATERIALS AND METHODS

Estuaries may be generally defined as semi-enclosed bodies where fresh water and sea water meet and through their mixing a salinity gradient is created. In relation to their salinity characteristics, estuaries in the northwestern Gulf of Mexico range from one extreme typified by the estuaries near the Mississippi River to the other represented by the Laguna Madre. Estuaries are generally described, in addition to their salinity range, by tidal amplitude, water temperature, bottom sediment type, vegetation types, species composition, productivity rates, etc. These features of estuaries are not narrow-range descriptors. Rather, large differences are the norm. As an adaption to these recurrent conditions of change, estuarine flora and fauna possess a degree of resiliency that is quite often underestimated. The floods and droughts that may come in any season or in any year make an estuary, at best, a rough neighborhood in which to live and raise a family. However, with all these vacillations, estuaries do possess common attributes that lie within a range, although very broad, that can be considered "normal." Of these attributes, freshwater content is generally agreed to be of prime importance, but questions of the proper volume, season(s), and duration of freshwater inflow to an estuary have not been agreed upon unanimously.

Management decisions in regard to altering the quality, timing, and quantity of freshwater inflow into estuaries require knowledge of the response patterns of estuarine communities to such changes. Through analysis of extant multi-year field data, actual ecosystem-level response patterns to natural salinity variations might become detectable. The knowledge thus gained could then be used to predict the effects that other proposed alterations would most likely produce. In addition, by assembling the extant data for individual estuaries, the extremes of fluctuations for the various biotic and abiotic parameters could be determined to give a "range of normalcy" for each estuary and provide a basis of comparison for predictive and monitoring purposes.

DATA SOURCES

To test the feasibility of describing individual estuaries, extant data (collected by three separate organizations for three separate "types" of estuaries in Alabama, Louisiana, and Texas) were used to construct a data base. These data were either obtained in a computer-ready form on tape, or computer files were created from field data to facilitate rapid computation, comparison, and automatic plotting of these computatations and/or comparisons.

CHARACTERIZATION RATIONALE

The proposed methodology consists of essentially three broad functional areas: (1) Data Assembly and Appraisal; (2) Ecosystem Characterization and Prediction; and (3) Impact Monitoring for Prediction Verification. Within each of these three areas there are a number of steps required as shown in Figure 1.

Data assembly consists primarily of literature review and acquisition of extant data available in the public domain. Examples of such data are those that have been generated in various studies sponsored by U.S. Federal agencies (e.g., Department of Interior, Bureau of Land Management Offshore Lease Studies), long-term monitoring programs conducted by state and Federal agencies, environmental impact assessments, and university or consultative studies of specific project areas. Data from such sources are frequently available in a computer-ready form and, therefore, immediately available for analysis. Those data not available in a computer-ready form are so entered and, thus, an expanded data base is created from disparate sources for analytical and comparative purposes.

Using this composite data base, inter- and intra-ecosystem evaluation and assessments may be conducted. These evaluations and assessments, because the data are in a rapidly

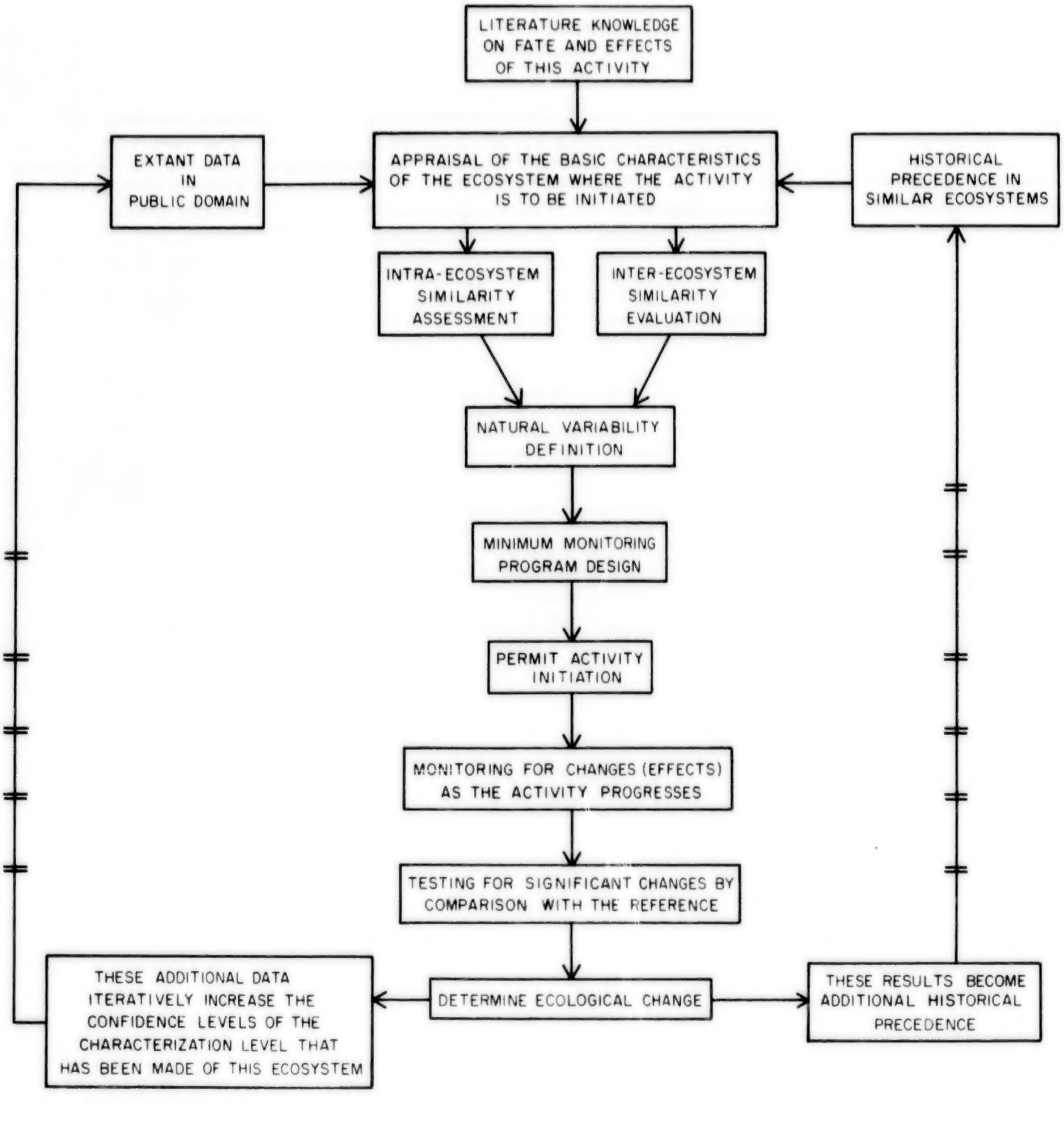
LITERATURE KNOWLEDGE ON FATE AND EFFECTS OF THIS ACTIVITY
EXTANT DATA IN PUBLIC DOMAIN
APPRAISAL OF THE BASIC CHARACTERISTICS OF THE ECOSYSTEM WHERE THE ACTIVITY IS TO BE INITIATED
HISTORICAL PRECEDENCE IN SIMILAR ECOSYSTEMS
INTRA-ECOSYSTEM SIMILARITY ASSESSMENT
INTER-ECOSYSTEM SIMILARITY EVALUATION
NATURAL VARIABILITY DEFINITION
MINIMUM MONITORING PROGRAM DESIGN
PERMIT ACTIVITY INITIATION
MONITORING FOR CHANGES (EFFECTS) AS THE ACTIVITY PROGRESSES
TESTING FOR SIGNIFICANT CHANGES BY COMPARISON WITH THE REFERENCE
THESE ADDITIONAL DATA ITERATIVELY INCREASE THE CONFIDENCE LEVELS OF THE CHARACTERIZATION LEVEL THAT HAS BEEN MADE OF THIS ECOSYSTEM
DETERMINE ECOLOGICAL CHANGE
THESE RESULTS BECOME ADDITIONAL HISTORICAL PRECEDENCE

Figure 1. Data input and procedural activities flow chart for estuarine characterization and minimum monitoring program.

queriable form, may be carried out by either individuals or groups working directly with the data base. Therefore, through utilizatation of information and data from these various sources, natural variability may be defined for a given area. Having characterized the area and defined its natural variability, an effective monitoring program can be designed. Because the general character of the area has been determined along with its natural variability, the monitoring program may be very selective in the number of parameters measured and as to the density of measurement. Therefore, it would be minimal in coverage but should provide high confidence detection of change.

Next, the activity is commenced, the monitoring program is commenced, periodic testing through comparison against the composite data base is conducted, and the level and magnitude of any ecological change that has occurred are estimated.

RESULTS AND DISCUSSION

SYSTEM SIMILARITY ASSESSMENT

Parameters that are considered to be important environmental factors in estuaries are water temperature, salinity, and substrate type. Comparisons based on these parameters are good indicators of the environmental similarity of separate estuaries. For this purpose, data relating to those parameters from the following estuarine areas in the Gulf of Mexico were used: Mobile Bay, Alabama; Timbalier Bay, Louisiana; and Lavaca, Copano, and Aransas bays, Texas. In order to assess the similarity of these five estuarine areas for use as examples for this discussion, seasonal water temperature and salinity patterns were determined.

Temperature

In Figure 2, the mean monthly values and one standard deviation about that mean are displayed for comparative purposes. Comparison of the displays show seasonal water temperature patterns to be essentially the same for all of the five bays (e.g., a low of from 10° to 12°C in January-February and a high of 28° to 30°C in July-August which represents an annual difference of approximately 18° to 20°C).

Salinity

The annual salinity patterns within the five bays differ substantially (Figure 2). Timbalier Bay is a fairly constant, high salinity bay described as ". . . . similar to many other bays along the Central Gulf Coast. It differs in that it is normally less affected by large rivers and is, thus, more saline" (Price 1979). Mobile Bay has a highly variable salinity range tending toward lower salinity with observed changes in freshwater discharge rate of ±10X occurring within a 15-day period (Schroeder 1978). Lavaca Bay is known to experience wide salinity fluctuations with a high salinity average. Armstrong and Hinson (1978) postulate that "Solunar Tides, though small, may provide the prime mechanism for water movement. . . " In the other two bays the annual salinity range is generally lower in Copano Bay than Timbalier Bay and higher in Aransas Bay than in Mobile Bay. It has been shown that river flooding changes salinity in the Copano-Aransas bays area from about 4 parts per thousand in Mission Bay to about 26 ppt in the vicinity of Mud Island (Brown et al. 1976).

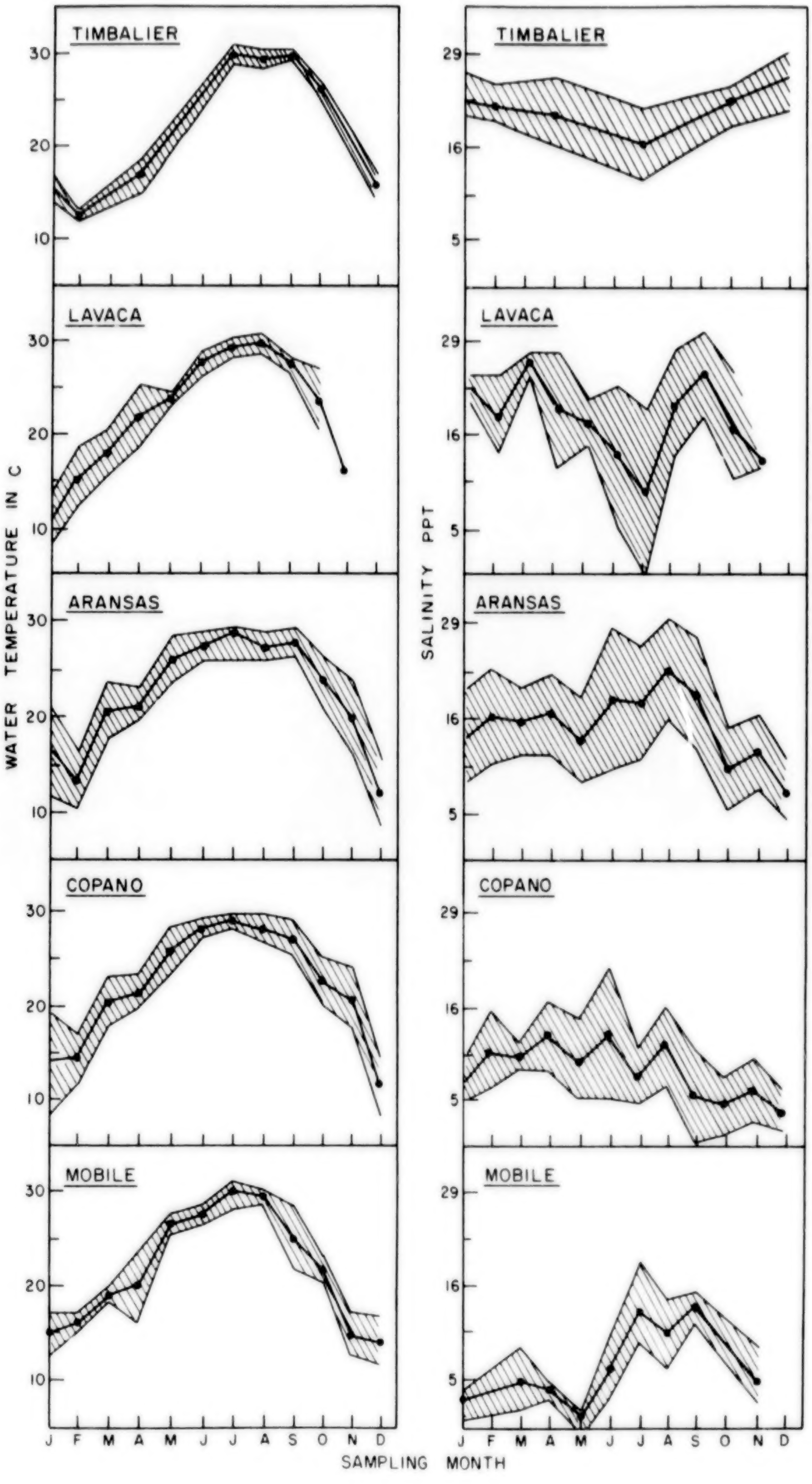

Figure 2. The mean monthly value and one standard deviation for water temperature (in centigrade) and salinity (in parts per thousand) for five bays in the Gulf of Mexico.

The sediment types in the five bays have been described through various studies. "The types of sediment found in Timbalier Bay were silt, sandy silt, silty sand, and sand (Jones and Williams 1979). Isphording and Lamb (1979) described the sediment types of Mobile Bay as "Most of the sediments in the bay are sands or clays or mixtures of the two. The percentages of silt are generally low, although large areas of the bay have some silt content." Aransas and Copano bays ". . . are floored by substrates composed of (1) mottled bay and lagoon mud with some shell, (2) oyster reefs and reef flanks, and (3) inter-reef mud with oyster shell" (Brown et al. 1976). Lavaca Bay consists of oyster reefs, bay sand with mixed shell, mud, and shell fragments (McGowen et al. 1976). There are essentially five major components common to all five bays: sand, mud, silt, shell fragments, and active oyster reefs.

Biota

For purposes of this paper an appraisal was carried out to determine the similarity of the habitat and inhabitats within five bays. This was not an attempt to precisely predict the type and magnitude of effects that a given activity would have, but rather to show that there is sufficient similarity between estuaries in the Gulf of Mexico to expect at least that similar activities in similar estuaries will produce similar results.

It has been shown that macroinvertebrate benthos populations are greatly influenced (e.g., species abundance, composition, etc.) by salinity, sediment type, and certain other habitat features (Parker 1956). In this paper a component of the benthos (e.g., polychaetes) was used as an example of the estuarine fauna for illustrative purposes. Because of their sedentary habits, polychaetes are especially good indicators of conditions, past and present. By dwelling in the bottom sediments they are placed constantly and intimately in contact with the most severe natural changes (e.g., salinity, dissolved oxygen) that occur in estuaries. Also they are located in the "sink area" of pollutant deposition and accumulation. They should be, therefore, early indicators of stressed environments.

A species spectrum for polychaetes taken from each of the five bays was constructed by ranking the mean abundance of each species and one standard deviation about that mean (Figure 3). These data were obtained over the following periods of time: 37 months for Lavaca Bay, 32 months for Copano and Aransas bays, 12 months for Timbalier Bay, and 12 months for Mobile Bay. They generally conform to the species spectrum pattern one might expect to find. In addition, Mackin (1971) and Harper (1973) have characterized the macroinvertebrate populations of the Gulf of Mexico as having lowest populations in summer and highest populations in spring and, although space in this paper does not permit display of polychaete populations in the five bays, they do when plotted generally conform to the pattern of seasonal abundance.

DEFINITION OF THE NATURAL VARIABILITY

Natural variabilities of coastal ecosystems are a measure of the environmental changes to which the resident biota are adjusted. If there are no persistent changes outside the limits of natural change (e.g.,

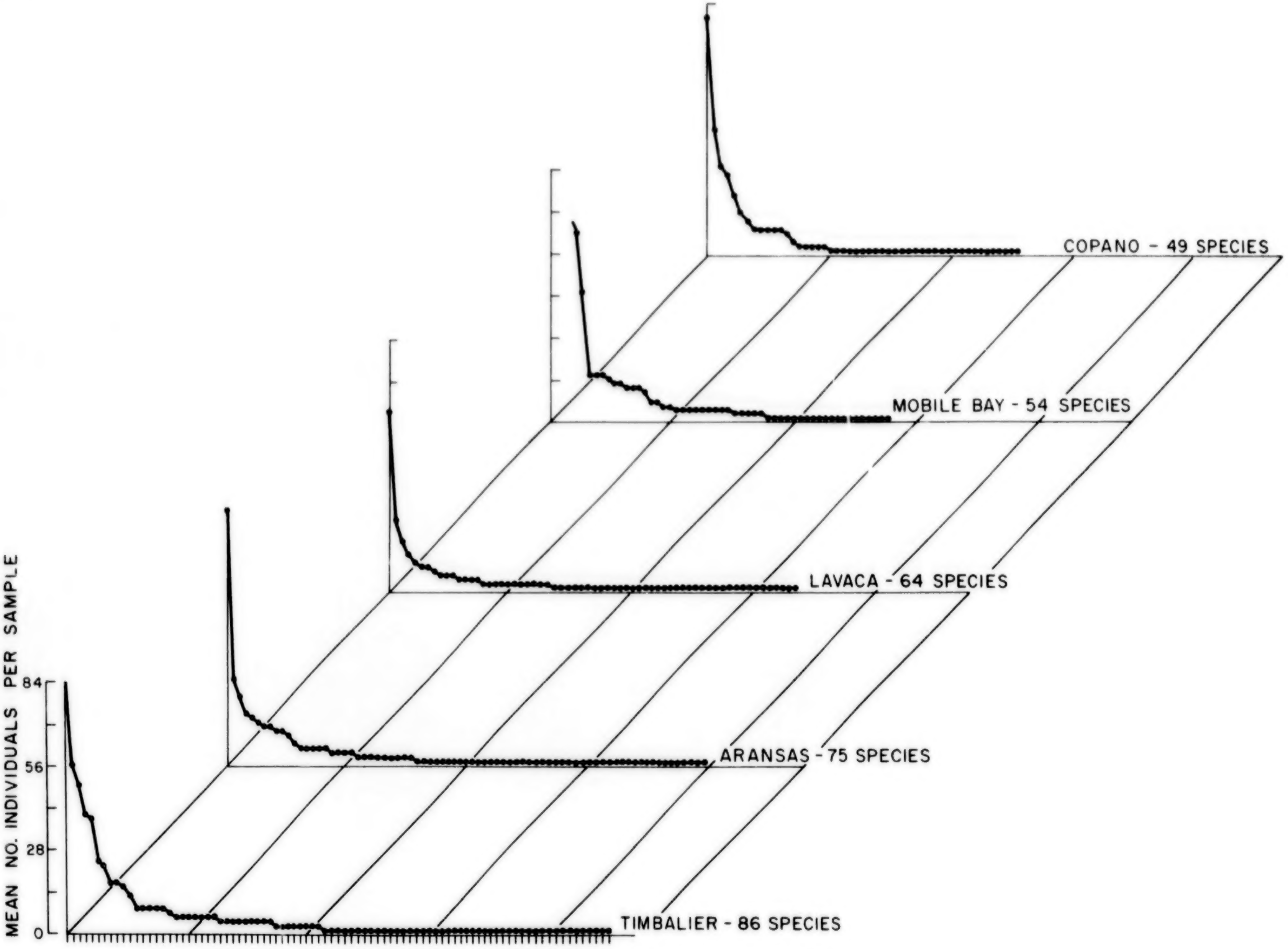

Figure 3. Species spectra for polychaetes from five bays in the Gulf of Mexico constructed by ranking the mean abundance of each species.

seasonally and/or annually) that occur, the community may be considered "healthy" or "normal."

Natural variability of biological communities can be determined statistically for a given ecosystem. The abundance and structure of the biota should vary within statistically defined limits. To detect and/or measure persistent decline or change, a reference standard is needed. For this purpose, statistical means and standard deviation are appropriate.

By definition, plus or minus one standard deviation includes approximately two-thirds of the measurements from which it is computed. The data used in the studies show deviations in environmental parameters which are larger than this value. This occurs in less then one-third of the measurements and therefore permits use of the one standard deviation as a reference for defining normality. In addition, the excursion of both the environmental and biological parameters beyond one standard deviation can generally be attributed to episodic natural events (i.e., floods, etc.). The data show, also, that biotic recovery from these events is both predictable and rapid. The question remains, however, as to whether natural variability limits are acceptable in detecting or controlling non-natural variations in the environment --e.g., inflow of natural or non-natural materials.

MINIMUM MONITORING PROGRAM DESIGN

Estuarine systems that have similar physical and chemical characteristics may be expected to have similar population structure characteristics (i.e., species abundance, richness, diversity, frequency distribution, etc.). Undesirable change, or damage, to the ecosystem should be shown by a change in these structural indices of the resident biota. It may be evidenced by changes in abundance and relative abundance (i.e., abnormal increases, abnormal scarcity and/or disappearance of one or more species). Such changes can be measured and quantified, thus providing a more direct and definitive means for detecting ecological change, or damage, than evironmental quality indices or standards.

JUDGING THE MONITORING DATA AND DETECTING DEVIATIONS

In an attempt to establish a "uniform regime" in which structural indices could be examined with data from one of the bays (e.g., Lavaca), only sampling stations that were in approximately the same water depth and substrate type were considered. The spatial variability of the stations within this regime was determined and compared to salinity levels along a transect from inner-bay to outer bay (Figure 4A). In addition, temporal variability was examined and variability at the species-level was determined based on data covering a four-year period (Figures 4B and 4C).

Similarity patterns for ten (10) stations located in the "regime" were examined. The inner-bay, mid-bay, and outer-bay stations display a uniform spatial gradient in species richness. This gradient appears to exist every season and, therefore, interpolation between sampling locations should be possible. Based on this type of spatial similarity evaluation a minimum number of stations selected for monitoring would consist of the mid-bay station as the principal monitoring station, along with occasional measurements at the

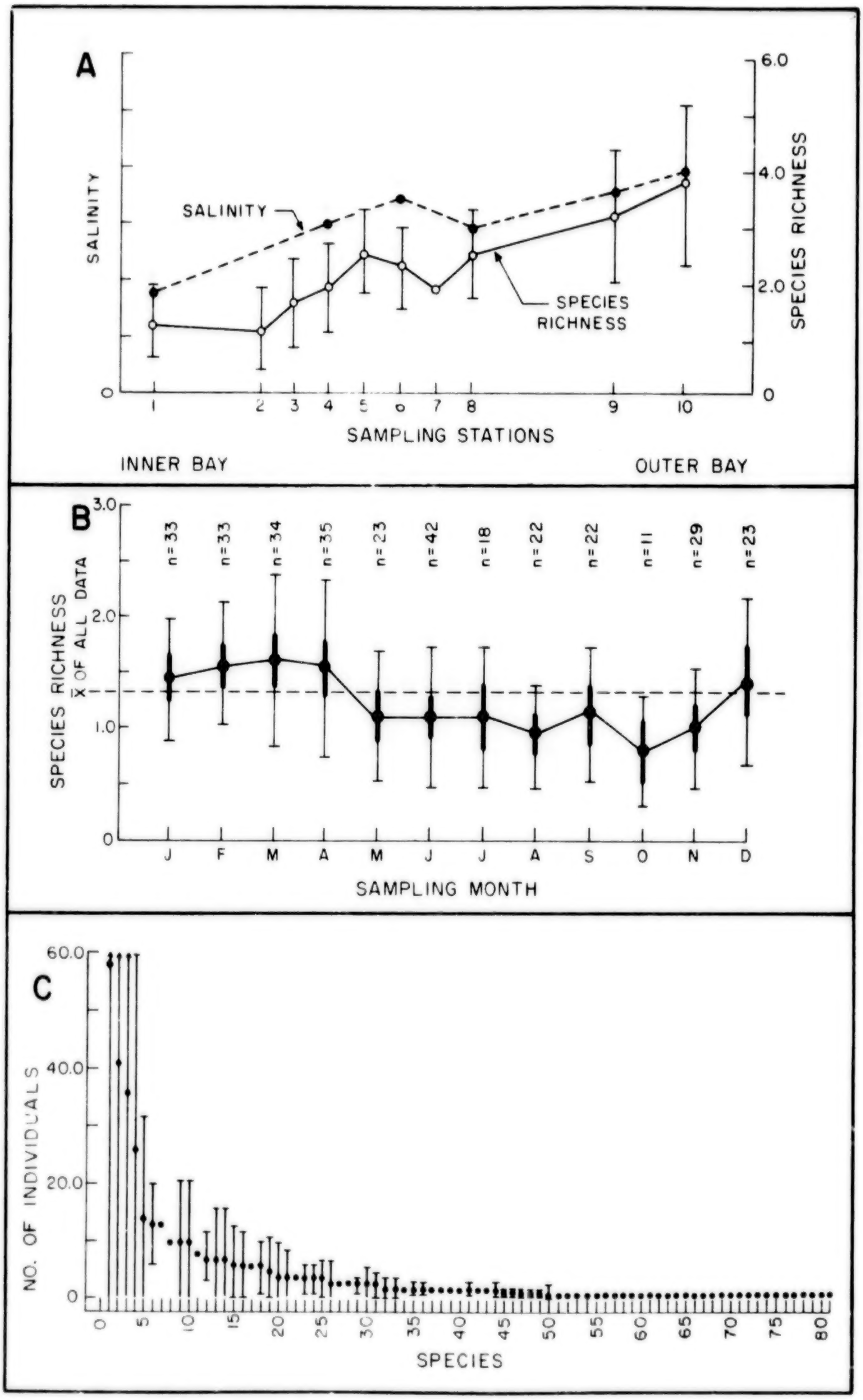

Figure 4. Displays of data relating to macroinvertebrates in Lavaca Bay, Texas showing influence of habitat parameters and population variability.

inner- and outer-bay stations for verification.

Figure 4B shows the seasonal variability patterns. The shape of the seasonality curve agrees with the expected behavior of the first half-year showing recruitment and growth, and the second half-year showing population decline, a pattern characteristic of macroinvertebrate populations in the Gulf of Mexico (Mackin 1971, and Harper 1973). Awareness of this cyclical pattern should enable one to reduce monitoring frequency of macroinvertebrates in the Gulf of Mexico and still monitor seasonal effects.

Figure 4C displays the mean abundance of each of the 81 benthic taxa at the mid-bay station. The all station mean was compared to that of inner-, mid-, and outer-bay stations. A gradient in abundance from outer-bay to inner-bay exists, even at individual species-level, which suggests that sampling the mid-bay station alone would give an "average value" for the benthic organisms in the bay. Therefore, the mid-bay station may be sufficient for system-level monitoring and may suffice as the principal monitoring station.

Based upon the data considered in this paper, June and November appear to be months of principal importance for seasonal monitoring. Initially, sampling should be conducted in other months for verification of seasonal monitoring adequacy. The selection of the additional time for sampling would be dependent upon the nature of the problem under study.

For illustrative purposes, the natural variability patterns (spatial, temporal, and species-level) are shown for polychaetes in Lavaca Bay. This, then, serves as a reference for gauging, in the future, deviations outside the limits of natural variability in the community. Therefore, data obtained from a monitoring program can be tested against this reference and, as long as they fall within the natural variability limits, the activity would not be considered detrimental. The spatial variability patterns established will aid in the immediate detection of localized point source effects which will show up as deviations from the normal gradient (Figure 5A). The temporal variability limits will aid in distinguishing transient fluctuations from persistent declining trends (Figure 5B). A shift in community structure is directly observable by comparison against the reference species spectrum (Figure 5C).

CONCLUSIONS

FEASIBILITY EVALUATION

In an evaluation of the feasibility of this approach, an attempt was made to consider scientific soundness and whether practical implementation is possible. Based on these considerations it appears that:

1. It is possible to determine effects directly by defining community structural indices and, using this as a reference framework to compare against data obtained from monitoring programs, to test for deviations that exceed natural variability. This is a more direct way to investigate actual impacts than by measuring water quality or chemical concentrations, etc. and indirectly inferring effects based on laboratory-determined cause-effect relationships.

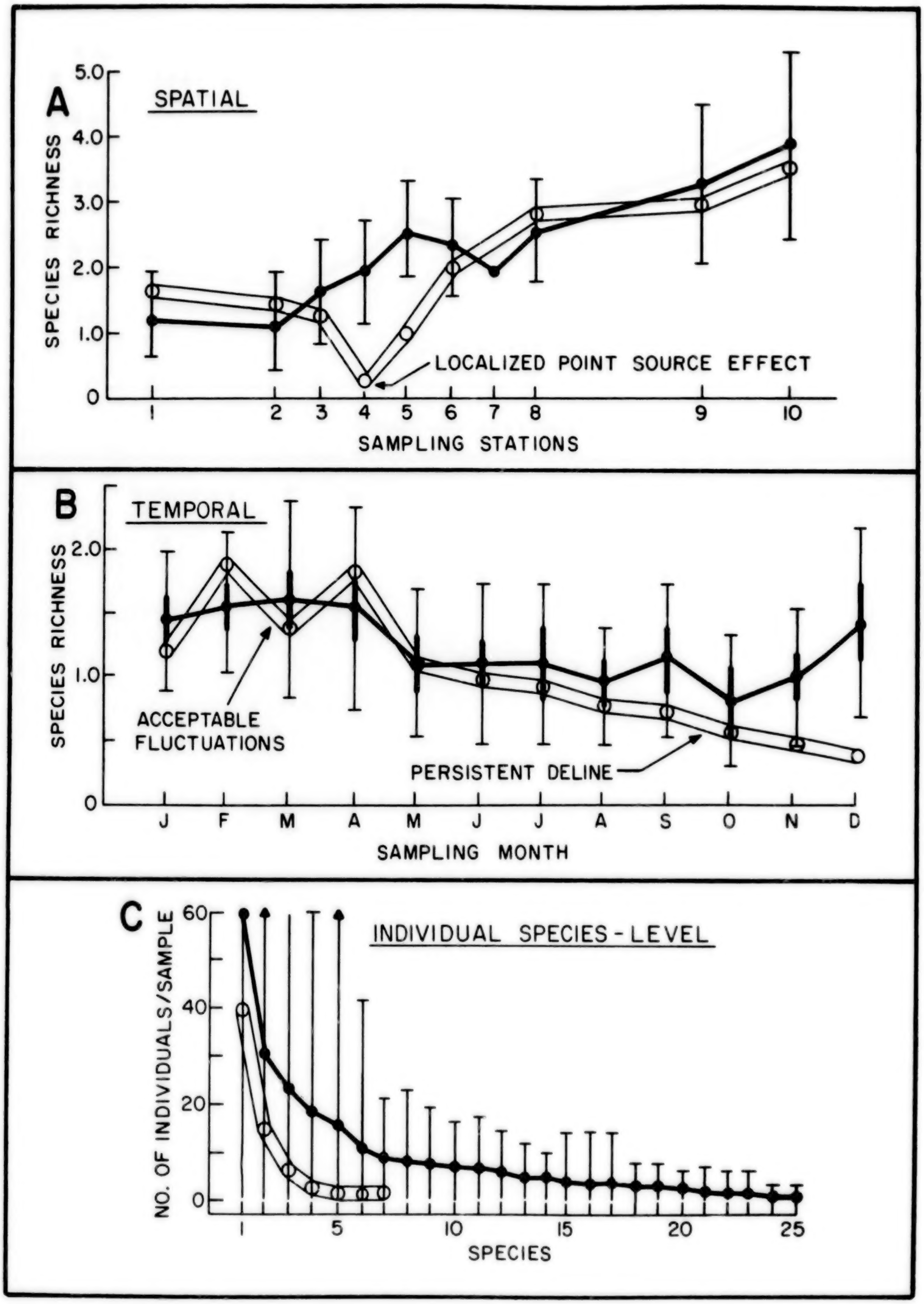

Figure 5. Spatial, temporal, and species-level compairsons between real data and hypothetical data.

2. Data are extant for many estuaries in the United States with adequate spatial and temporal density to permit initial definitions of the natural variability patterns of most habitat and inhabitant components. Such initial definitions would be improved as new data become available from the concurrent monitoring program that is conducted as a part of this methodology.

3. Data, freely accessible in a computer-ready form, can be repeatedly and rapidly evaluated by a number of scientists employing computer-assisted techniques. Through analysis/display of extant data, and those developed in future programs, errors or wrong impressions inherent when interpreting narrative reports could be eliminated. This provides a method for characterizing and monitoring estuaries that is more dynamic and direct than those commonly used.

4. By determining the similarity of given ecosystems (one in which a development or a change has occurred and another where a similar activity is to be carried out), a basis for impact prediction based on historical precedent can be developed. Where similarities are high, inter-ecosystem extrapolation of effects can be made with confidence levels adequate to predict that unacceptable ecological changes are either likely or unlikely to occur. The ecological risks taken are considered to be within acceptable limits because the prediction is based on records of actual field-level reponses to the same type of activity, and safeguarded by the monitoring program that is conducted while the activity progresses.

5. A minimum monitoring program can be designed, based on an analysis of the similarity patterns within the ecosystem where the activity is to be initiated and, thus, reduce the spatial and temporal sampling frequency required.

6. Many types of resource use activities have been carried out in the past within a number of different types of ecosystems, and these provide opportunities to measure actual long-term cumulative effects. Even though pre-activity baselines at these sites may not have been recorded, it is possible through after-the-fact case histories to detect cumulative effects. Such case histories indicate tolerance limits for: (1) different types of activities, (2) carried out at varying levels of intensity, and (3) in ecosystems with different and/or similar habitat and inhabitant characteristics.

BENEFITS AND WEAKNESSES

The primary benefit to be derived from this approach is that it takes advantage of available field knowledge of actual ecosystem-level response to various resource use activities. The concept presented here provides a method for at least predicting the possible effects a given type of activity would be expected to produce at sites having characteristics similar to those where a similar activity has been carried out. The criteria for defining ecosystem similarities, combined with a minimal monitoring program imposed, produce a system whereby risks could be predicted and changes gauged to insure that damage does not go undetected. This is a practical method that should be more reliable in averting environmental damage as compared with the indirect methods of environmental assessment that are practiced today.

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SANTEE-COOPER REDIVERSION: PROJECTED IMPACTS ON FISHERY RESOURCES AND WILDLIFE HABITATS

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ABSTRACT

The fresh water from the Santee River drainage basin was diverted through the Santee-Cooper hydroelectric plant into the Cooper River in 1942. This increased the average flow in the Cooper River from 72 cubic feet per second (cfs) to 15,600 cfs, and concomitant sediment resulted in a tremendous increase in shoaling in Charleston Harbor. The U.S. Army Corps of Engineers has initiated a project to alleviate this shoaling problem by rediverting most of this fresh water back into the Santee channel and reducing the average weekly flow in the Cooper River to approximately 3,000 cfs. This rediversion is scheduled to be completed in 1982. It is projected that fish and wildlife resources will be subjected to substantial impacts as a result of rediversion. Highly productive oyster and clam beds will be displaced or destroyed, as will valuable shrimp and finfish nursery areas. Severe reduction of freshwater flows into the Cooper River drainage will result in the displacement of freshwater and brackish marsh vegetation by saltmarsh plants; conversely, increases in freshwater flows into the Santee River drainage will cause salt marsh and brackish marsh vegetation to be succeeded by freshwater plants. These vegetative changes will cause profound changes in the wildlife populations of these two river drainages.

INTRODUCTION

The original Santee-Cooper Diversion Project was constructed and is operated by the South Carolina Public Service Authority. Its major feature was the impoundment of the Santee River and the diversion of most of its water to the Cooper River basin to take advantage of the greater fall in the Cooper basin for generating electricity. Prior to diversion in 1942, the Santee River had the fourth largest discharge on the Atlantic coast of the United States (U.S. Army Corps of Engineers 1975). This original diversion project increased the average annual flow of the Cooper River at Pinopolis from 72 cfs (2 m^3/sec) to 15,600 cfs (441.5 m^3/sec), while reducing the average annual flow of the Santee River at the present site of Wilson Dam from about 15,500 cfs (438.7 m^3/sec) to 2,230 cfs (63.1 m^3/sec) (U.S. Army Corps of Engineers 1975).

Increased shoaling in Charleston Harbor was an unanticipated result of the Santee-Cooper diversion project. The average annual amount of material dredged from Charleston Harbor increased from 500,000 cubic yards (382,300 m^3) before diversion to 10,000,000 cubic yards (7,646,000 m^3) a few years after the project was completed. Studies since 1942 have revealed that the greatly increased inflow of fresh water to the harbor interacts with the tidal inflow of saline water from the Atlantic Ocean to form density currents which entrap sediments and create vast shoals. This large increase in shoaling resulted in a tremendous increase in maintenance dredging requirements for Charleston Harbor (Mathews et al. 1980). Thus, in 1966 the Corps of Engineers proposed to reduce the shoaling problem in Charleston Harbor by rediverting most of the original Santee River flow back into the Santee basin. The Santee-Cooper Rediversion Project was authorized by the River and Harbor Act of 1968 (U.S. Army Corps of Engineers 1975).

The Santee-Cooper Rediversion Project (Figure 1) proposes to reduce shoaling in Charleston Harbor by rediverting water to the lower Santee River so that flows in the Cooper River are limited to a weekly average of 3,000 cfs (84.9 m^3/sec), an amount determined by Corps of Engineers' sediment modeling studies to be insufficient for the formation of density currents and the entrapment of sediment. The Corps of Engineers' sediment modeling studies for Charleston Harbor have been the subject of controversy among physical scientists in recent years, with some contending that the Santee-Cooper Rediversion Project will greatly reduce shoaling in the harbor while others maintain that the sediments are largely ocean-derived and that the Rediversion Project will have little effect on shoaling (Van Nieuwenhuise et al. 1978).

At present, the Cooper River estuary is typically a stratified estuary with the salt wedge extending up to river mile 17 and the salinity gradient ranging from 27 ppt at the mouth to permanent fresh water at river mile 30 (Figure 1) (Mathews and Shealy 1978). During low flow conditions in fall of 1978, when freshwater input approximated those quantities expected after rediversion, stratification was very weak or not present at all in both the Cooper and Wando rivers (Burrell and Carson 1978; Shealy and Bishop 1979).

The Santee River bifurcates at approximately river mile 15 (Figure 1). Most of the river flow (85 percent) moves through the north branch and therefore salinities are lower here than in the south branch (U.S. Army Corps of Engineers 1975). The permanent freshwater line in each distributary occurs at approximately river mile 11. The lower reaches of each branch are thoroughly mixed, with salinities usually greater than 25 ppt near the mouths (Kjerfve 1976).

Periodically, when rainfall is excessive in the Santee drainage basin, water is released at Wilson Dam to control water levels in Lake Marion. This results in vertical salinity stratification near the mouth or, in extreme cases, in fresh water

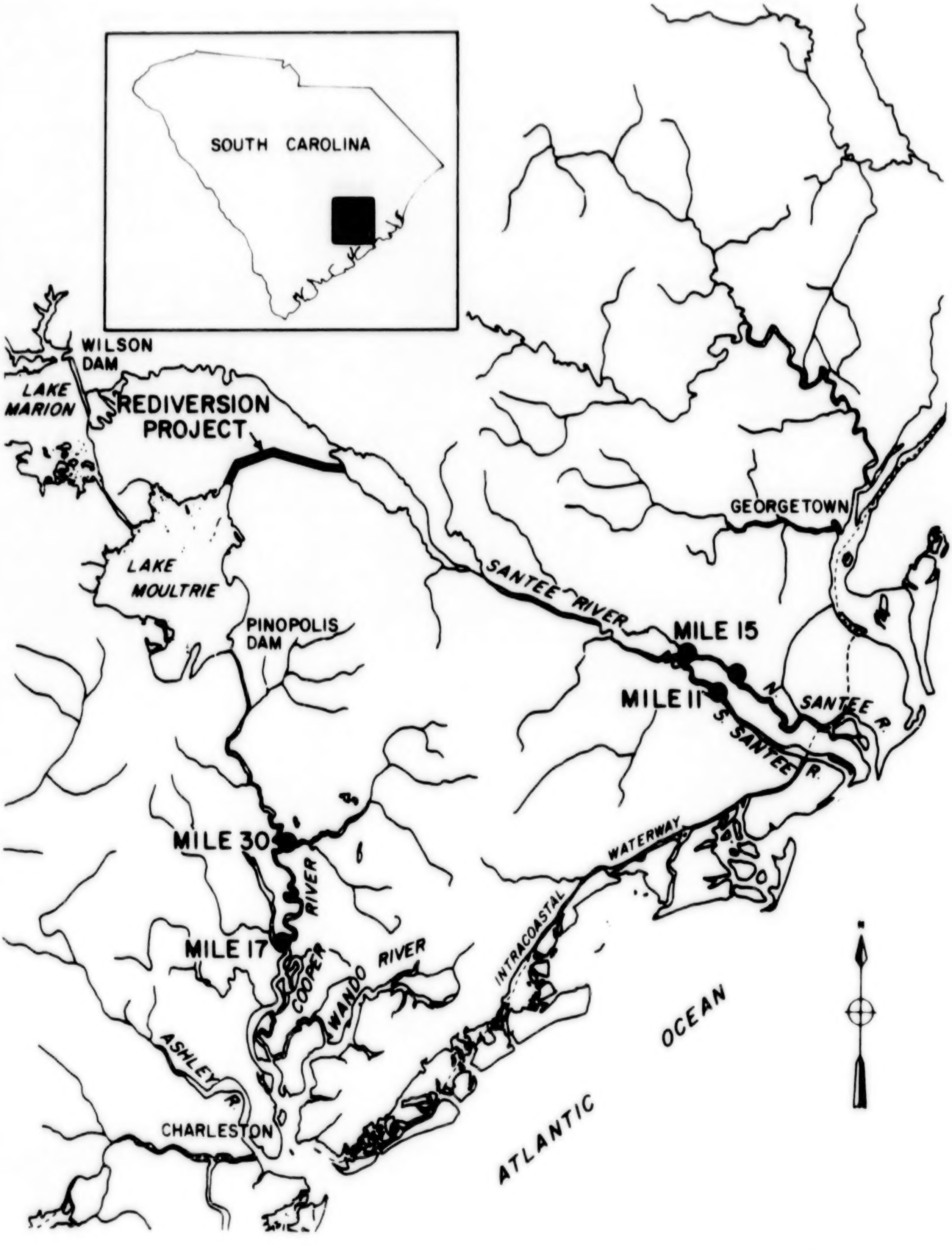

Figure 1. The Cooper and Santee estuaries, South Carolina, showing areas affected by the rediversion project.

extending nearly a mile off shore on the surface (Burrell 1977).

Several general studies of the biota of the Cooper and Santee estuaries have been completed. One, an investigation of the oyster resources of South Carolina by J. D. Battle (1891), provides good distribution data that precedes diversion. Bears Bluff Laboratories (1964) conducted a year-long study of the Cooper and Santee systems (1963-1964) to assess oyster, fish, shrimp, crab and plankton populations when "rediversion" was being investigated as a possible solution to siltation in Charleston Harbor. More recently, the South Carolina Marine Resources Research Institute has conducted intensive multi-year chemical, physical, and biological surveys of the Cooper (1973-1979) and the Santee (1975-1977) river systems (S.C. Wildlife and Marine Resources Department 1979). A number of other works more specific in scope or limited in duration have focused on various components of these two estuaries. These include surveys of anadromous fishes (S.C. Wildlife and Marine Resources Department 1979), oysters and clams (Burrell 1977, Rhodes et al. 1977, Burrell et al. 1980), benthic invertebrates (Calder and Boothe 1977, Calder et al. 1977), fish eggs and larvae (Wakefield and Lyons 1975), and flora (Batson 1974, Batson and Blackwelder 1974; Statler 1974). Most of these reports are summarized in Sandifer et al. (1980). These data provide considerable baseline information on living components of these estuaries, but leave such things as community structure and interactions with physical and chemical attributes of the marine environment subjects of conjecture.

Several ongoing biological studies, designed to help assess the impacts of the Santee-Cooper Rediversion Project, are being conducted by the U.S. Fish and Wildlife Service and the South Carolina Wildlife and Marine Resources Department. One study is designed to assess population characteristics and migration patterns of blueback herring in the Santee River system, while a second study is investigating spawning activities and requirements of this species in both the Santee and Cooper river systems. A one-year effort to determine forage patterns of major predators, with emphasis on striped bass, is being conducted in lakes Marion and Moultrie. A vegetative cover mapping effort is ongoing for both the Santee and Cooper portions of the Rediversion Project area, and this effort will expand into a long-term monitoring study of vegetative changes brought about by project completion. In addition to these studies by state and Federal agency personnel, researchers from The Citadel are studying ecological succession in impoundments of the Cooper River drainage that will be affected by the Rediversion Project.

FISHERY RESOURCES

Both the Cooper and Santee systems serve as important fish nursery grounds. Those species of most commercial and recreational importance are the penaeid shrimp; flounders (Paralichthys spp.); sciaenid fishes such as spot (Leiostomus xanthurus), seatrout (Cynoscion spp.), red drum (Sciaenops ocellata), kingfish (Menticirrhus spp.), Atlantic croaker (Micropogonias undulatus), and black drum (Pogonias cromis); and the blue crab (Callinectes sapidus). Sturgeon (Acipenser spp.), herring and shad (Alosa spp.), and striped bass (Morone saxatilis) are important anadromous species which spawn in the freshwater portions of these rivers. The American eel (Anguilla rostrata), a catadromous species, utilizes these waters extensively. Adults of many of these and other finfish mullet (Mugil spp.), bluefish (Pomatomus saltatrix), and sheepshead (Archosargus probatocephalus) are caught by both recreational fisherman and commercial gill net operators in these estuaries (Bears Bluff Laboratories 1964, Shealy et al. 1974). Sturgeon nets and shad nets are also fished at the mouth of the Santee, this being one of the few viable Atlantic sturgeon fisheries remaining in the United States (S.C. Wildlife and Marine Resources Department 1979). Hard clams (Mercenaria mercenaria) and oysters (Crassostrea virginica) are extensively harvested from lower Santee beds, while subtidal oysters from the Wando River are transplanted as seed to other areas (Manzi et al. 1977, Rhodes et al. 1977, Burrell et al. 1980). Blue crabs are harvested commerically in Charleston Harbor and in the Santee They are also a prized recreational species in the Charleston Harbor System.

Commercial harvesting of penaeid shrimp maturing in these estuaries takes place in the sea in close proximity to the various river mouths, with the exception of North Santee Bay which is opened in fall for commercial taking of white shrimp, Penaeus setiferus. Recreational harvest of shrimp is permitted in these estuaries and large quantities are landed with a variety of gear.

Spawning stock used by the Dennis Wildlife Center Striped Bass Hatchery is obtained at the base of Pinopolis Dam on the Cooper River. This hatchery distributes some 55 million striped bass and hybrid bass larvae throughout the country (S.C. Wildlife and Marine Resources Department 1979). The blueback herring (Alosa aestivalis) is the most important forage fish for the landlocked striped bass populations in lakes Marion and Moultrie, and they are recruited via the locks at Pinopolis Dam. Two other clupeid striped bass prey species, the threadfin shad (Dorosoma petenense) and gizzard shad (Dorosoma cepedianum), enter the lakes via these locks.

WILDLIFE RESOURCES

Land in the Santee portion of the project area is largely undeveloped woodland and marsh, with a major portion of the basin south of the Santee River comprising the Francis Marion National Forest. This forest contains 249,412 acres (100,937 ha) and is bounded by the Santee River on the north, the Atlantic Intracoastal Waterway on the east, the Wando River on the south, and Lake Moultrie and the Cooper River on the west (U.S. Department of Agriculture, Forest Service 1977). Much of the Santee Delta area is in state ownership, including the 25,000-acre (10,100 ha) Santee Coastal Reserve and the 17,845-acre (7,210 ha) Tom Yawkey Wildlife Center. The Cape Romain National Wildlife Refuge, containing 55,066 acres (22,250 ha) of barrier islands, marshlands, bays, and tidal creeks, stretches for 15 miles (24 km) along the South Carolina coast between the mouths of the Santee and Cooper rivers.

Wildlife habitat abounds in the Santee portion of the project area, including varying-aged pine stands, mixed pine-hardwoods, mixed hardwoods, seasonally flooded hardwoods, cypress-tupelo swamp, managed impoundments, abandoned rice fields, cultivated fields, and pastureland (McKenzie et al. 1980). Ecotonal zones, areas of interspersion between adjacent habitats, are abundant in this area and support large and diverse wildlife populations. Bird and mammal populations are especially diverse, with waterfowl and white-tailed deer (*Odocoileus virginianus*) providing the base for extensive recreational use of the area.

Land in the Cooper River basin has been subjected to considerable development pressure. The Greater Charleston Metropolitan Area surrounds the mouth of the river, and the lower half of the basin has undergone considerable development for residential and industrial use. Agricultural and forestry activities constitute the primary land uses in the upper portion of the basin.

Wildlife habitat in the Cooper basin is of fairly high quality, although it differs considerably from that found in the lower Santee basin. Terrestrial habitats have been reduced by development pressures, and mammal and other terrestrial animal populations have declined accordingly. Waterfowl and wading bird habitats, however, particularly in the form of abandoned ricefields, are both abundant and of high quality.

Terrestrial species of recreational importance in the rediversion project area include the white-tailed deer, turkey (*Meleagris gallopavo*), gray squirrel (*Sciurus carolinensis*), fox squirrel (*S. niger*), raccoon (*Procyon lotor*), and opossum (*Didelphis marsupialis*). Of particular recreational interest are the numbers and diversity of waterfowl species that utilize the impoundments during the winter months. Dabbling ducks occurring most commonly include mallards (*Anas platyrhynchos*), gadwalls (*A. strepera*), blue-winged teals (*A. discors*), green-winged teals (*A. crecca*), pintails (*A. acuta*), and wood ducks (*Aix sponsa*). Diving ducks include the ring-necked duck (*Aythya collaris*) and the canvasback (*Aythya valisineria*). Associated with the waterfowl in impoundment and marsh habitats are the American coot (*Fulica americana*), Virginia rail (*Rallus limicola*), king rail (*R. elegans*), yellow rail (*Coturnicops noveboracensis*), and sora rail (*Porzana carolina*) (McKenzie et al. 1980).

Endangered and threatened species recorded from the rediversion project area include eastern cougar (*Felis concolor cougar*), southern bald eagle (*Haliaeetus l. leucocephalus*), Arctic peregrine falcon (*Falco peregrinus tundrius*), eastern brown pelican (*Pelecanus occidentalis carolinensis*), Bachman's warbler (*Vermivora bachmanii*), red-cockaded woodpecker (*Picoides borealis*), American alligator (*Alligator mississippiensis*), Kemp's ridley turtle (*Lepidochelys kempi*), green turtle (*Chelonia mydas*), hawksbill turtle (*Eretmochelys imbricata*), leatherback turtle (*Dermochelys coriacea*), loggerhead turtle (*Caretta caretta*), and shortnose sturgeon (*Acipenser brevirostrum*) (National Fish and Wildlife Laboratory 1980).

PROJECTED IMPACTS ON FISHERIES

Impacts on fishery resources, as well as other wildlife, are anticipated. Alterations of salinity regimes in the two basins will affect fisheries significantly and, based on present knowledge, offer the best predictive factor. Other physical and chemical changes, such as current flow, sedimentation, and pollutant concentrations, will be reflected in distribution and abundance of the fisheries species involved; however, data to even conjecture on the degree of impact are lacking.

Loss of some if not all of the hard clam and oyster beds in the lower Santee can be expected. Prior to diversion, these species were not present in the lower Santee, and on occasions of large runoff, shellfish resources in adjacent growing areas suffered significant mortalities (Lunz 1938). After diversion, freshwater oyster kills were reported in the Santee (Burrell 1977). Loss of seed oysters in the Wando may also occur with an increase in salinity in Charleston Harbor. Predators such as the oyster drill (*Urosalpinx cinaria*, *Eupleura caudata*) and boring sponge (*Cliona* spp.) and the oyster pathogen, *Perkinsus marinus*, appear to be controlled by low salinity and thus permit survival of subtidal seed oysters in the Wando under current conditions (Burrell and Carson 1979). New shellfish habitat may occur from salinity-and sediment-related changes; however, based on present knowledge, this seems a very remote possibility.

Penaeid shrimp support the State's most valuable fishery. Nursery grounds for the two most important shrimp species, the white (*Penaeus setiferus*) and the brown (*P. aztecus*), are present in both the Santee and Cooper systems. Juvenile white shrimp appear to prefer low salinity (10 ppt), while young browns are found in greater numbers in higher salinities (10-20 ppt) (Gunter et al.1964). Shealy and Bishop (1979) found white shrimp to be more abundant in the Cooper River than in other South Carolina estuaries studied, and reported that young white shrimp were associated with Brazilian elodea (*Egeria densa*), a submergent plant which can tolerate salinities only up to 10 ppt. How this nursery ground will be affected by higher salinities is not known. It could be displaced upstream and be supplanted by a brown shrimp nursery downstream. This would be the ideal situation, but what actually occurs will be known only after rediversion. Juvenile brown shrimp are more abundant in the Santee system and particularly in the south branch (Bears Bluff Laboratories 1964). With lowered salinity, the best situation would be replacement upstream by more productive white shrimp nursery grounds and displacement downstream of the brown shrimp nursery. The possibility remains, however, that salinities may be so low as to preclude any large-scale use of the Santee system by either shrimp species.

Migration of anadromous fish species would be expected to increase in the Santee River concurrent with greater freshwater flow. Recruitment of sufficient spawning stock for striped bass hatchery activities, however, will depend on spawning runs being established in this river. Provisions have been made to build a hatchery at the Santee dam to take advantage of such a run, and contingency plans have been made to ensure maintenance of the Cooper River run should it be necessary (U.S. Army Corps of Engineers 1975). A fish lift will be installed at the Santee power plant to assure passage of forage species into the lakes. There is some concern that the considerable expanse of fresh water below the lift might divert migrating fish prior to their reaching this device. Contingency plans call for moving forage fish into the lakes via the locks at Pinopolis, if necessary. American shad (Alosa sapidissima), Atlantic sturgeon (Acipenser oxyrhynchus), and shortnose sturgeon migrations should be strengthened in the Santee and will probably cease altogether if any are present in the Cooper.

American eel stocks in the Santee would be expected to increase and those in the Cooper system to decrease. Eels appear to be strongly influenced to move from main channels to other bodies of water by freshwater flow. This stimulus occurs at present from the many connections of old rice fields adjacent to the Cooper.

Finfish nursery grounds in the Cooper system probably will be compressed at the upper end of this estuary and to some degree offset by additional areas in the Santee. Adult coastal marine fishes will increase in the Cooper River system while low salinity-freshwater species will occupy a greater portion of the Santee. Whether or not this will offset a concomitant decrease in other species in each estuary will be known only after rediversion.

Blue crab abundance may increase to some degree in the Cooper estuary because larger areas of suitable salinities (30 to 10 ppt) will be available (Van Engel 1958; Tan and Van Engel 1966). Stocks in the Santee estuary will probably decrease.

PROJECTED IMPACTS ON WILDLIFE

Impacts on wildlife and wildlife habitats are anticipated in both drainage basins. Aquatic habitats will be greatly increased in the Santee portion of the project area, but there will be a net loss of salt and brackish marsh habitats. Approximately 9,000 acres (3,636 ha) of bottomlands will be inundated either permanently or for extended periods (U.S. Army Corps of Engineers 1975). The numerous waterfowl impoundments in the lower Santee basin will succeed from brackish to fresh water over time, which will cause shifts in waterfowl species usage. Large numbers of trees are expected to die because of their intolerance to permanent or extended inundation. Terrestrial wildlife species will lose habitat, but other species will likely benefit from the project. Wood ducks, for instance, will realize substantial benefits from the increased acreage of flooded bottomland hardwood forest habitat.

Impacts on wildlife in the Cooper River drainage basin will not necessarily be the reverse of those found in the Santee, as might be expected. Acreages of aquatic habitat will not be greatly reduced as a result of rediversion, although the character of these habitats will shift considerably as a result of changes in salinity patterns. Large-scale saltwater intrusion will result in major aquatic vegetation changes through natural succession as freshwater plants are replaced by salt and brackish species. Managed impoundments will likely become more brackish over time, while some unmanaged impoundments may dry up as water levels in the Cooper River basin decline slightly. Some reduction in waterfowl habitat will occur as current overflow areas will be almost eliminated by freshwater flow reductions. The quality of aquatic habitats in the Cooper River basin will be reduced somewhat as project-caused flow reductions diminish water quality by increasing the retention time of pollutants in the system.

Impacts on endangered and threatened wildlife species are not easily projected. The long-term impacts on most of these species occurring in the project area are likely to be negligible. One species, however, the American alligator, will likely realize a net increase in its preferred habitat in the Santee basin as a result of the project, which will probably result in a slight population expansion in that area.

CONCLUSIONS AND RECOMMENDATIONS

Projecting biological impacts of an activity with the magnitude of the Santee-Cooper Rediversion Project is an awesome task. It is indeed a tenuous exercise to relate predicted changes to one factor--salinity. It may be much too naive to suggest that fairly even trade-offs between the two estuaries will occur. We have attempted to highlight project-related areas of greatest concern to those with interest in or responsibilities for the welfare of living resources found in the area. We feel that additional research prior to rediversion should be directed at understanding more of the attributes necessary for continued successful production of important fishery species, and that an indepth look at the influence of impoundments in the area on high-interest fish and wildlife species should be undertaken.

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METHODS OF COMPUTATION AND ECOLOGICAL REGULATION OF THE SALINITY REGIME IN ESTUARIES AND SHALLOW SEAS IN CONNECTION WITH WATER REGULATION FOR HUMAN REQUIREMENTS

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ABSTRACT

The Western part of the Black Sea, the Azov Sea, the Aral Sea, and the northern part of the Caspian Sea and some of their rivers, deltas and bays (the Danube, Dniester and Dnieper, the Don and Kuban, the Amu-Darya, and Syr Darya and the Volga, Tereck , and Kura, respectively) are rather typical as to the hydrographical and ecological conditions. These areas are representative of complicated worldwide systems where there is a confluence and interaction of fresh and salt waters affecting the river-delta bay-(estuary)-and coastal zone areas of the sea. Historically any type of river delta is the heart of a rich, productive ecosystem that has been forming for thousands of years. A delta receives nutrients from upstream and more importantly, produces, circulates, and processes an additional (about 70 percent) nutrient increment within its fresh-brackish water body and this subsequently largely influences the rich productivity of the marine estuarine bay area and even the outer coastal zone furthest downstream. More recently man has been a factor in altering the nature of such systems by regulation and withdrawal of river-delta water supplies for municipal, industrial, and agricultural use. Detailed studies and data gathered over the past few decades provide substantial cause for alarm for the life of the delta bay coastal zone systems under the practice of continued water developments without a better understanding of their real nature.

Four universal characteristic zones of the river to sea transition may be observed in deltas and bays: (1) the upper part containing chiefly river water; (2) the intermediate part presenting the main cone of the mouth; (3) the lower part where the influence of sea water is noticeable; and (4) the pregulf and gulf where the water exchange between the delta and the bay takes place. A hydrofront is formed in the bay at the outlet from the delta where the fresh, brackish, and sea waters meet. The halocline and thermocline are clearly manifested here. In the course of salinity intrusion caused by decreased outflow the width of these zones will decrease on account of widening of the sea water zone. In Russia the results of the studies have shown over the last twenty years that the water withdrawals for agricultural, municipal and industrial needs increased from 20 to 50 percent of the natural average runoff. Because of this decreased outflow serious successive degradations of fish and wildlife resources have been recorded for the last 4 to 10 years

under the influence of increasing salinity intrusion (up to 100 miles from the sea) which eventually affected municipal and agricultural water supplies and, in some cases, even destroyed the diverted water supply itself. Besides this, the effects of the pollution loads have been increased, progressively forming stagnant waters in deltas, bays, and coastal zones. The salinity of water in some deltas increased from 0.1 ppt to 1.2 ppt to Cl', the volume of nutrients discharged into bays decreased about 20 to 55 percent, the catch of fish became about 8 to 10 times less than before water diversions. In some coastal zone areas the losses of sustaining biota lead to irreversible effects on the biological structure of plankton and benthos communities, including algae, crayfish, mussels, and fish such as Black Sea mackerel, sturgeon, pike, perch, mullet, stripped bass, etc.

This experience is directly pertinent to the problems faced today by, for example, the San Francisco Bay-Delta ecosystem, where the net flow has decreased by comparison with historical data records about two-fold. Consequently, in the present San Francisco Bay-Delta area there is now 6 to 10 times increase in salinity in the delta, 2 to 4 times, and 2 to 3 times in Suisun and San Pablo Bay, respectively, during some seasons and years.

If the volume of river runoff is decreased to a level of 75 percent of the long-term average, the salinity in Suisun Bay will reach, especially in summer, almost the value of salinity of the San Pablo Bay in 5 to 10 years, which will cause the death of fresh-and slightly saltwater flora and fauna, and will ultimately destroy all irrigation and municipal systems fed by the delta.

Two projects are being developed in Russia for the prevention of salinification of some deltas as well as of the Azov Sea: (1) the construction of a fixed sea water check dam completely preventing the entrance of sea water into the delta and changing the delta into the freshwater lake; and (2) a dam with a built-in restraining canal ensuring constant connection with the sea but limiting the entrance of sea water to an amount which not only preserves the acceptable salinity conditions but also facilitates the future freshening of bays. Both projects are of considerable interest. The construction of a fixed water check dam is preferable from the point of freshwater supply, while the construction of a dam with a restraint canal assures a better preservation of natural conditions in the bays and adjacent maritime area, creating conditions for free navigation without sluices.

The proposed method of water exchange regulation does not disturb the ways of fish migration and the movement of river sediment and nutrient load, which have been forming for ages, and it preserves the transportation connection between basins. This method is of special significance for regions, where it is difficult to single out the nonperiodic component of water exchange in tidal bays and estuaries as, for example, the delta of the Murrey River, the Chesapeake Bay, the lagoons near Venice and the bays of San Pablo or Suisuin in the San Francisco Bay Area. Computation of the exact requirements for maintaining each system in a near-natural state requires detailed monitoring of salinity intrusion under a variety of outflow-hydrographic conditions along with special considerations of often neglected topographic, oceanographic, and meteorologic factors.

INTRODUCTION

The discussion in this article is based upon the results of research carried out over many years in the Black and the Azov Seas and their tributaries. In addition, a brief assessment is made of recent developments in the Nile River and the San Francisco Bay-Delta as parallel examples of the universal application of the ecological effects of man's water development schemes (Table 1).

Besides, during the years 1957-1976, the first author has been dwelling on the general problem of optimizing water exchange between shallow basins such as the Danube-Dniester coastal zone lagoons and the Dnieper and Dniester estuaries of the northwestern part of the Black Sea (Figure 1). An introduction to some results of these investigations and some procedures for calculation of water and salt balance, as well as methods for regulation of their regimes, will undoubtedly be of great interest far beyond the outcome for the water basins of southern Russia.

The necessity of developing new territories and the reconstruction of the environmental conditions of old ones is connected with an extensive development of the productive forces of society, which is inevitably accompanied by an increase of water consumption and a considerable territorial redistribution of water resources (Almazov 1962, Bronfman 1975, Dolgopolov et al. 1973, Kelly et al. 1977, Meleshkin et al. 1976, Vendrov 1970).

From this point of view, the intermediate links of complex systems of river-liman(bay)-sea and river-sea types react most keenly upon quantitative and qualitative changes of water balance caused by intensifying agricultural, industrial, and municipal water consumption (Osmer 1973, Rodzianko and Cherkashin 1976).

DATA ANALYSIS

The solution of the above problem is based on the knowledge of the the principal correlation between components of the water and salinity balance of shallow marine basins and the influence of particular water consumers upon the environment as a whole (Rozengurt 1958, 1964, 1967, 1969, 1972, 1974; Rozengurt and Sitneko 1973; Rozengurt et al. 1976).

The western part of the Black Sea the Azov Sea, and some of their rivers, deltas, and bays (the Dniester and Dnieper, the Don and Kuban, respectively) are typical as to hydrographical and ecological conditions (Bolshakov et al. 1964). It is a well known fact that the resulting hydrological and hydrobiological regime of investigated systems depends primarily upon the volume of fresh, brackish, and sea waters annually taking part in water and salt exchange between different reaches of these systems (Vinogradov et al. 1966). Thus, if decisions are made to utilize some additional part of the annual freshwater runoff, one might expect an increasing volume of sea and brackish water taking part in salt exchange (Figure 2). As a consequence, the increase in salinity from the nearest coastal zone will be measurable throughout the delta or some of its parts (Table 1).

Observed seasonal variations of salt exchange are much greater and their range depends on a number of factors, such as winds, tides, distance from the sea straits, run-off of the previous season or month, and

TABLE 1

SOME MORPHOMETRIC AND HYDROLOGICAL FEATURES OF SEVERAL ECOSYSTEMS OF THE TYPE: RIVER (DELTA)--LIMAN (BAY)--SHELF ZONE OF THE SEA

Basin	Area Km^2	Volume Km^3	Historical Runoff Km^3	Total Water Withdrawals (%)	Salinity (g/l) Historical Range	Present Range	Salinity Average Historical	Present
The Black Sea	$423\cdot10^3$	$537\cdot10^3$	350	40-44	-	-	-	-
North-western part	$68.9\cdot10^3$	$1.91\cdot10^3$	264	33-37	13-18 (surface) 15-18.3 (bottom)	14-19 16-20.5	16.5	18.5
Under influence of Dnieper River	$10\cdot10^3$	192	54	40	1.0-12.0 5-17.0	1.-15.0 10-19.0	14	17.0
Dnieper drainage basin	$503\cdot10^3$	-	-	-				
Dnieper Liman	800	3	54	40	0.1-9.7 0.5-13.0	0.2-13.7 1.0-18.0	3.0	6.5
Dnieper River delta	350	?	54	35-45	0.1-0.8	1.0-10.0	0.3	1.0
Dniester drainage basin	$72\cdot10^3$	-	-	-				
Dniester Liman	408	0.7		40	0.2-4.5	1.5-12.0	1.4	3.5
Dniester River delta	120	?	10	35-45	0.2-0.5	0.3-1.0	0.3	0.9
Danube drainage basin	$817\cdot10^3$	-	-	-				
Danube River delta	$5.640\cdot10^3$	2.23	198	15-20	0.1-0.5	0.1-1.0	0.3	0.5
The Azov Sea	$38\cdot10^3$	324	43	50	8.5-11.5	12-16.0	10.5	15.0
Don drainage basin	$420\cdot10^3$	-	-	-				
Don River delta	540	?	29.4	35	0.05-3.0	0.1-6.0	0.3	1.0?
Kuban River delta	$4.3\cdot10^3$	?	13.6	79	0.05-3.0	0.5-14.2	0.3	1.0?
The Mediterranean Sea[1]	$2501.5\cdot10^3$	$3842\cdot10^3$	430	?	33.8-39.3	33.8-39.3	38	38
Nile drainage basin	$2870\cdot10^3$	-	202	64	-	-	-	-
Nile River delta	4000?	?	85	80(1965)	0.01-5.0	0.1-28.0	?	?
The San Francisco Bay Area[2]	$1.14\cdot10^3$	8.34	-	-	-	-		
Sacramento-San Joaquin River delta	159	1.57	38	50	0.01-1.8	0.5-3.0	?	?
Suisun Bay	150	0.50	38	50	0.01-2.0	1-14	?	?
Carquinez Strait	14	0.23	38	50	0.1-2.5	1-20	?	?
San Pablo Bay	296	1.05	38	50	?	10-30	?	?
North San Francisco Bay	230	3.39	38	50	?	15-33	?	?
South San Francisco Bay	291	1.60	?	?	?	10-32	?	?

[1] Hydrology of the Mediterranean Sea, 1976, "Hydrometeoizdat,"ed., Leningrad.

[2] Kelly, D.W., Description of the Sacramento-San Joaquin Estuary, 1966 Fish Bull. 133, p. 10.
Conomos, T.J., Properties and Circulation of San Francisco Bay System, San Francisco Bay, The Urbanized Estuary, 1979, pp 77-89;
Physical and Chemical Properties of San Francisco Bay Waters, Open File Report 79-511, 1969-1976, U.S. Geological Survey;
Variation and Control of Salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay, 1931, Dept. Water Resources, Bull. #27,
Economic Aspects of Salt Water Barrier, 1931, Dept. Water Resources, the State of California, Bull. #28.

Table 2. Hydrochemical characteristics for the Dnieper and Dniester Rivers under natural and regulated conditions (by Almazov 1962)

Parameter	Historical Average Dnieper;	Dniester	Predicted Losses (%) After Regulation Dnieper;	Dniester
Flow (Km^3)	52	10	32	35
Ionic Constituents (10^3 Tons)				
Ca^{++}	2,341	622	27	42
Mg^{++}	503	161	22	47
$Na^+ + K^+$	481	239	54	49
CL^-	681	343	39	13
$SO_4^=$	1,208	549	32	37
HCO_3^-	8,179	1,882	28	45
	13,401	3,842	33	39
Nutrient Constutuents (10^3 Tons)				
(Si)	145.4	42.7	32	30
(NO_3, NO_2, NH_4)	24.0	6.2	(+29)	(+25)
(PO_4)	1.7	0.4	19	13
(Fe)	7.3	0.4	42	39
	178.4	49.7	18	15

Figure 1

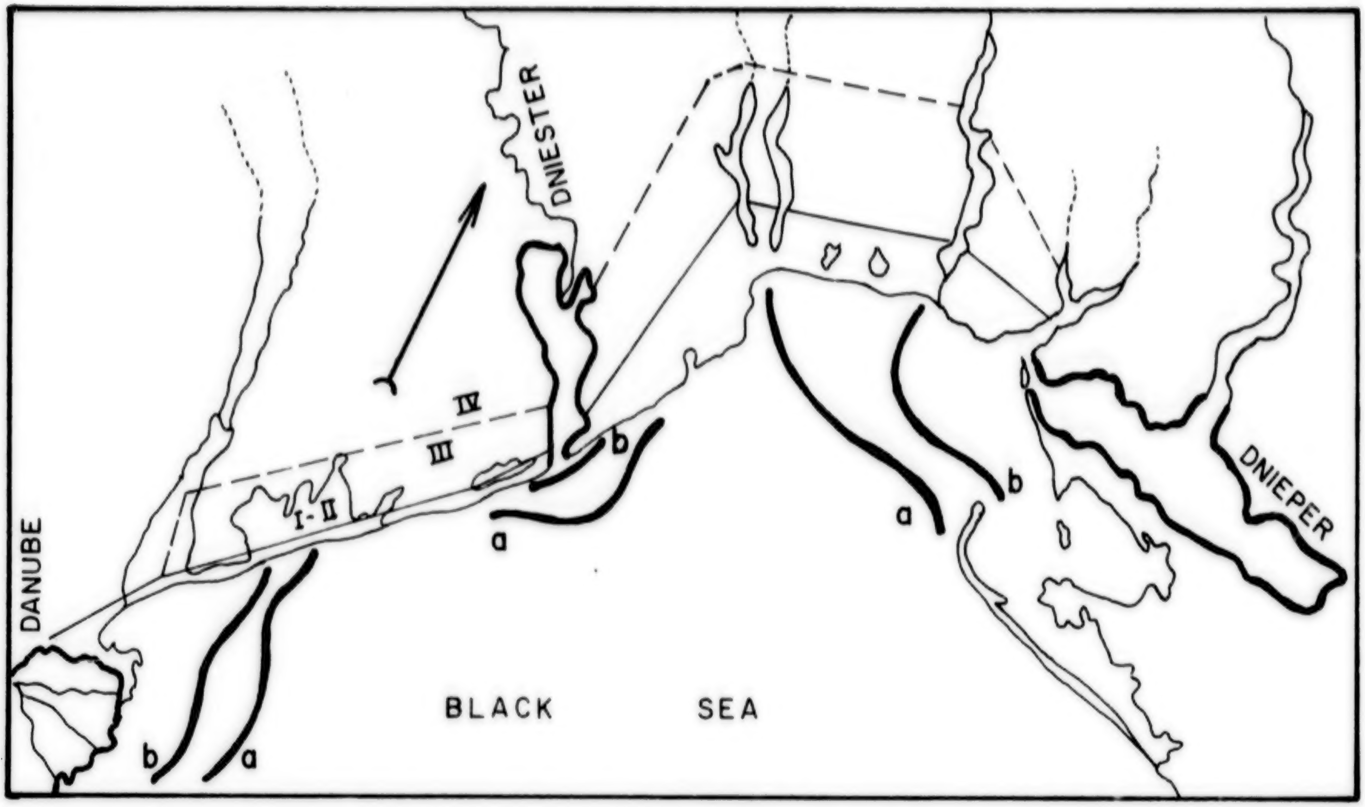


Figure 1. The location of the major limans (bays), liman-lagoons and estuaries of the northwestern part of the Black Sea. (A liman is a small harbor situated in a bay or estuary at the mouth of a river.) (a) the average distribution of hydrofronts in 1956-1966 and (b) 1968-1976 (the last period is during a time of extensive outflow regulation of rivers). I-II-III-IV traces of canals from the Danube River till the Dnieper limans.

Caption for Figure 2.

Dependences: A(a) and B(a) - the component (N) of fresh balance of the Dniester and the Dnieper Limans, respectively from rivers outflow (Q KM^3/year).

A(b) and B(b) - The liman "buffer" outflow (W_1), forming into Site 4, and the sea inflows (W_2), forming in front of the strait from N KM^3/year.

$A(C^1)$ and B(C) - the salinity (S o/oo c^{-1}) of the liman flows participating in the salt exchange from N, W_1, and W_2 for the Dniester and Dnieper limans where $W_1 = W^x + K$, N: $W_2 + = W^{x2} - K_2$ (N); $N = p + Q - E$, K_1, K_2 - probably of liman and sea currents in the strait. W - volume of water exchange only under wind's activity.

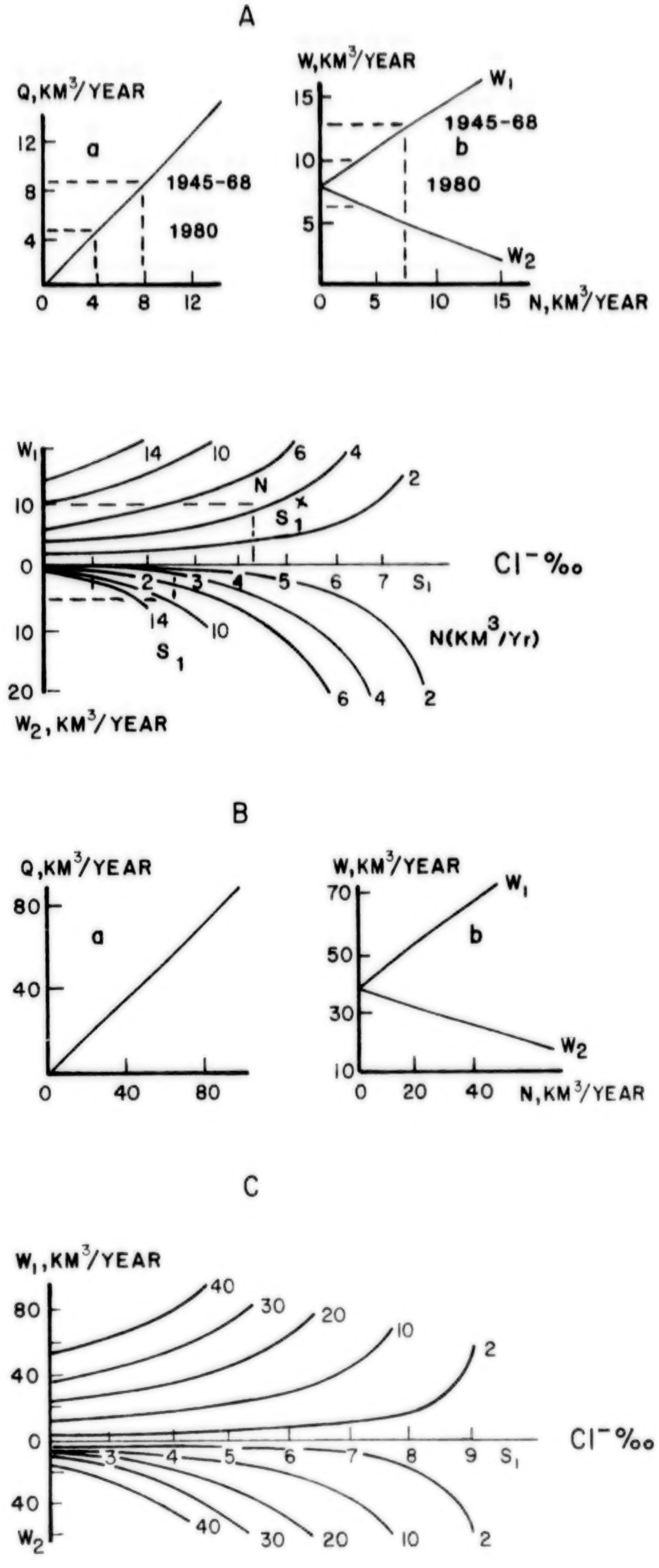
$$S_1 = \frac{W_2^x S_2 + W_r S_r}{W_2^x + N}$$

Where W_r - river outflow; S_r - salinity of river water, $>S_L$- salinity (Cl^-) of liman

A. S_1 (1945-1968) S_1^x (1980) - 2 times under 50% river outflow left for Dniester. S_L (1980) S_L (1945-1980) - 3 times (2.7 o/oo Cl^-).

B. The same for the Dnieper liman, i.e. S_L 1980 $> S_L$ about 2 times

Figure 2


A
Q, KM³/YEAR
a
1945-68
1980
0
4
8
12
W, KM³/YEAR
b
W₁
W₂
1945-68
1980
0
5
10
15
N, KM³/YEAR
W₁
14
10
6
4
2
N
S₁
x
10
0
Cl⁻‰
1
2
3
4
5
6
7
S₁
14
10
S₁
N(KM³/Yr)
10
20
6
4
2
W₂, KM³/YEAR
B
Q, KM³/YEAR
a
80
40
0
40
80
W, KM³/YEAR
b
W₁
W₂
70
50
30
10
0
20
40
N, KM³/YEAR
C
W₁, KM³/YEAR
40
30
20
10
2
80
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0
Cl⁻‰
3
4
5
6
7
8
9
S₁
40
W₂
40
30
20
10
2

so on. From this point, four characteristic zones of the river-to-sea transition may be observed in deltas and bays (Figure 3): (1) the upper part containing chiefly river water; (2) the intermediate part presenting the main cone of the mouth; (3) the lower part where the influence of sea water is noticeable; and (4) the pre-gulf and gulf where the water exchange between the delta and the bay takes place. A hydrofront is formed in the bay at the outlet from the delta where the fresh, brackish, and sea waters meet. The halocline and thermocline are clearly manifested here. In the course of salinity intrusion caused by decreased outflow, the width of these zones will decrease on account of the widening of the sea water zone.

The lack of data to understand these systems and to make strictly scientific predictions from the very beginning for decisions on water resources development, dredging deeper channels, and so on, seems to lead to conflicts between the demands of water users and that of the environment all over the world at the present time.

Briefly, this conflict results from misunderstanding which might have the following sources. Historically, any type of river-delta is the heart of a rich, productive ecosystem that has been forming for thousands of years. A delta receives ionic and nutrient constituents (Table 2) from upstream and, more importantly, produces, circulates, and processes an additional (about 70 percent) nutrient increment within its fresh-brackish water body. This subsequently largely influences the rich productivity of the marine-estuarine bay area and even the outer coastal zone furthest downstream (Laevastu and Hela 1970, Odum 1971). More recently, man has been a factor in altering the nature of such systems by regulation and withdrawal of river-delta water supplies for water users.

From the above point, the main mistake among water developers all over the world is the opinion that fresh water emptying into the bays or shallow coastal zones is an absurd waste and needs to be fixed. Although any essential change in the course of this vital bloodstream (such as artificial channels, dams, or ditches) or in the quality of its fluids (salt intrusion, sewage disposal, agricultural wastes) are leading to change, much of which has already been shown to be detrimental to social and economical, as well as ecological, systems (Vendrov and Diakonov 1976).

Such specialists prefer extensive water withdrawals for agricultural, municipal, and industrial needs on the basis of the prognosis of increased water demands for the foreseeable future. In this matter, no account is taken of the fact that each river has a certain natural limit beyond which man's water supply activity causes a breach in the ecological balance and the geomorphological regime between the river, the delta, and the contiguous sea areas (Aleem 1972, Rozengurt and Sitneko 1973, Rozengurt et al. 1974, Vendrov 1970).

Needless to say that if the Dnieper and Dniester estuaries, the Azov Sea, and the San Francisco Bay had not received at least 100, 20, 120, and 50 km^3 of fresh water, respectively, during the last ten years, and if one accepts that irreversible consumption was equal or not more than 15 percent, this means that millions of tons of organic materials and silt never reached the deltas, limans (bay), and adjacent coastal waters.

Figure 3

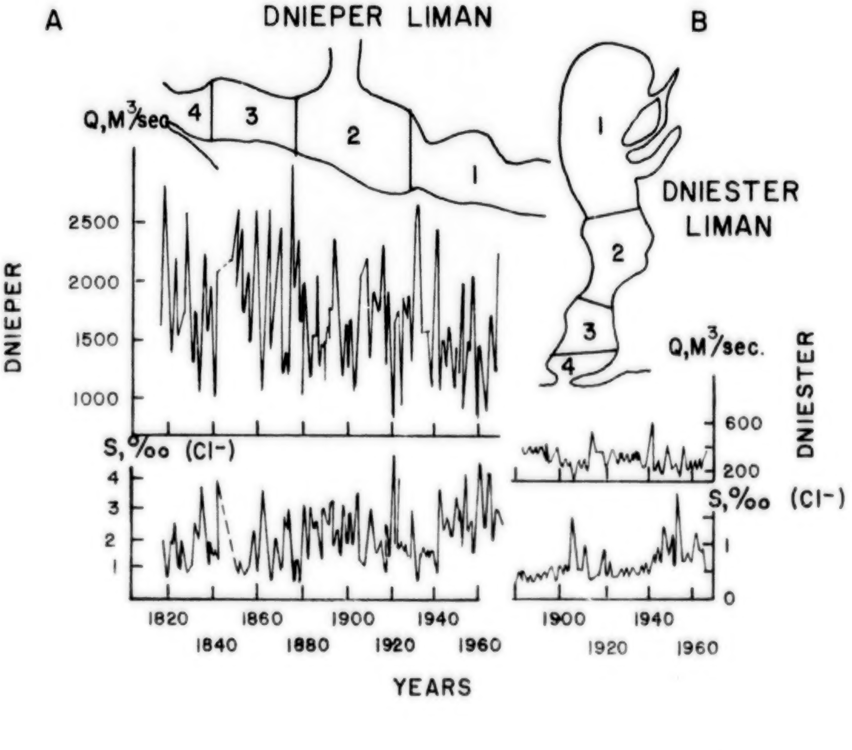


Figure 3. Chronological variations of salinity (o/oo Cl$^-$) of the central part (2) of the Dnieper (A) and the Dniester (B) limans and outflow of the Dnieper and the Dniester rivers.

During the last two decades, the anthropogenic factor of decreasing runoff has been considerably aggravated by the total reduction of precipitation and run-off in some river basins (for example in Europe in 1972 and in western North America in 1977). Thus, the imposition of both man and climatological factors began to develop negative consequences for aquatic life of large areas which are directly pertinent to the problem faced today in different parts of the world (for example, the Nile, Po, Volga, and others).

From this point, the main enemy and the first undesirable consequence of controlling the runoff of the rivers is the salinification of the estuarine areas in the Azov Sea (Figure 4) in which brackish water formerly predominated. This process of salinification has been progressing since the early 1960's after erecting a lot of dams for reservoirs in the river basins during the preceding 8 to 12 years.

On the basis of special statistical analysis of data gathered during about 30 years under unsteady salt conditions, computation of salinification and the time for its establishment for four basins has been performed by the following equation (Some details for calculation of each parameter in Equation 1 are available from Rozengurt 1969, 1974, Rozengurt and Tolmazin 1971, 1975):

$$S = \frac{q}{p} + Ce^{-pt} \qquad (1)$$

$$\text{where} \quad q = \frac{1}{v}(W_r S_r + W_2 S_2) \qquad (2)$$

$$p = \frac{1}{v} n_1 \qquad (3)$$

where S is the average salinity of the liman or the Azov Sea; S_2, W_2 is the average salinity and volume of water entering the liman or the Azov Sea from the Black Sea through the straits; S_r, W_r is the average salinity and volume of river runoff into the liman or sea for different probabilities; V is the volume of water in the liman (or the Azov Sea); and C is the constant value defined from the condition S = S.

Calculated salinity for limans (Table 3, Figure 5), a limited area of the Black Sea (Table 4) and for the Azov Sea (Table 5) for probability of outflow 95 percent are reflective of the present conditions of salt content under withdrawals more than 25 percent from the average flow. For example, in the Dniester and the Dnieper liman salinity increased about 2 and 3 fold; in the north part of the Black Sea, about 1.2 fold; and for the Azov Sea, 1.6 fold.

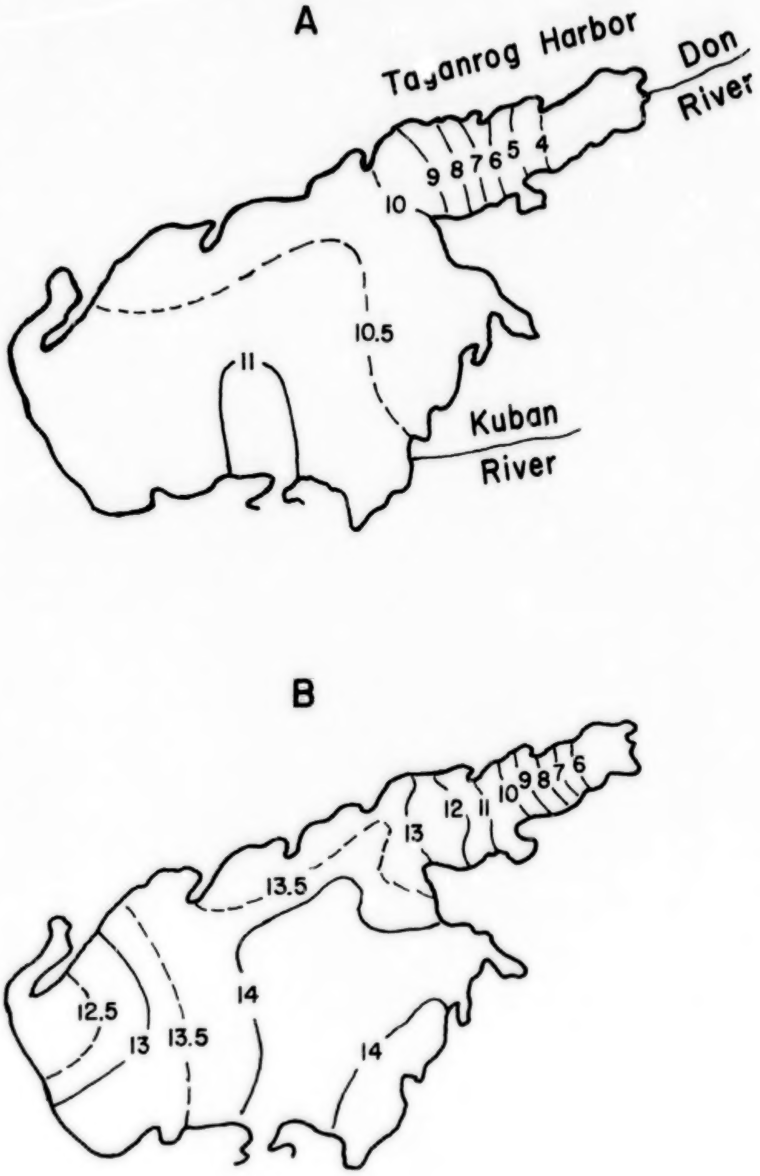
If the fresh component (N, Figure 2A) of water balance becomes negative (i.e., evaporation will be more than the sum of runoff and precipitation) the limans will turn into salty sea bays. The same result might be observed for the Azov sea if evaporation exceeds the volume of runoff and precipitation in this basin, and the northern part of the Black Sea will reach the present salinity of its western part.

In addition, the initial salt-water invasion at the bottom through ship channels came to be persistent. At the bottom of about 8 to 10 meters, salinity was 1.4 ppt about 100 to 120 km upstream from the sea in the Dnieper (Figure 6, in our case 45 to 60 km upstream from delta) and about 2 ppt a distance of 30 km into the Dniester Bay area (channel depth of about 6 m). That, in turn, led to stagnant conditions in some parts of the deltas and upstream for several kilometers as well as in the

Table 3. Probability forecasts of time required to establish different salinity regimes by water regulation in the Dniester and Dnieper Limans (bays) (by Rozengurt 1974).

The Characteristics of Runoff		Km^{3Q} /year	Calculated Characteristics	
			Cl °/oo	years
		DNIESTER LIMAN		
Probability,	%			
	50	8,43	1,0	---
	75	6,87	1,4	0,4
	90	5,65	1,7	0,5
	95	5,04	2,2	0,6
Regulated Flow (from 75%)		4,26	2,6	0,7
Sanitary Flow		1,58	5,6	1,4
Maximum Regulated Flow		0,63	7,8	1,9
Full Withdrawals		0	10,3	2,4
		DNIEPER LIMAN		
Probability,	%			
	50	55,1	1,6	
	75	44,9	2,6	0,4
Regulated Flow (from 75%)		11,9	5,2	0,7
		10,0	5,6	0,8
Maximum Withdrawals		5	7,2	1,0
		3	8,1	1,8
Full Withdrawals		0	9,8	1,9

Figure 4



THE AZOV SEA

Figure 4. Spatial distribution of Azov Sea salinity. (A) Historical, 1931-1951. (B) Following extensive upstream water regulation, 1976, (after Bronfman 1976).

Figure 5

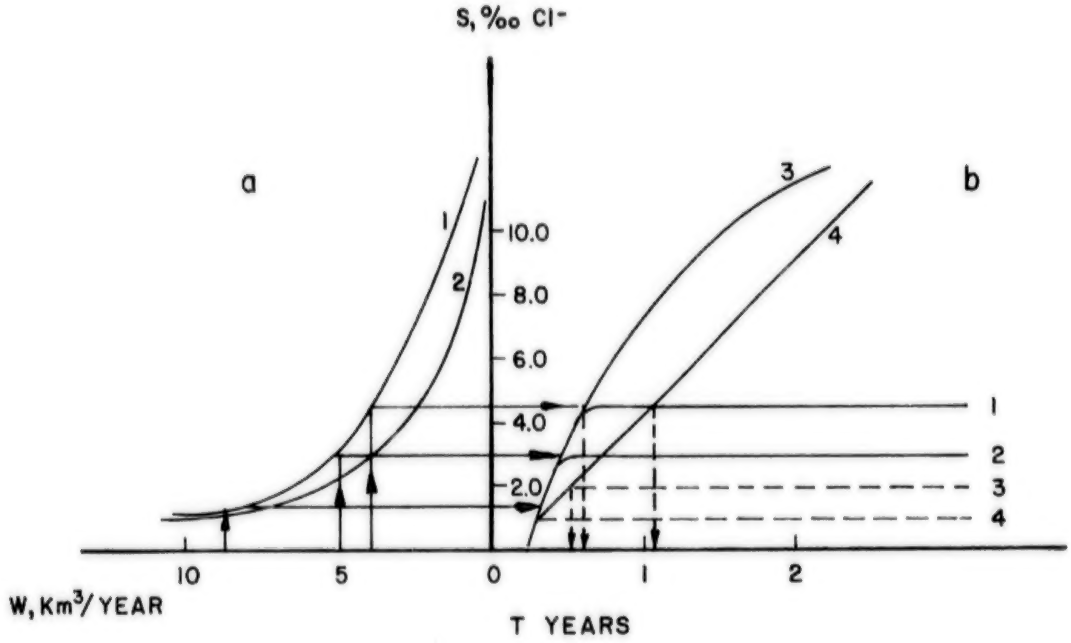


Figure 5. Dependence of the salinity of Dniester Bay on Dniester River runoff and time of its appearance: (a) under restraining channel (2) and without channel (1); (b) under channel (3), without channel (4), without flow from bay, Km^3/year.

Figure 6

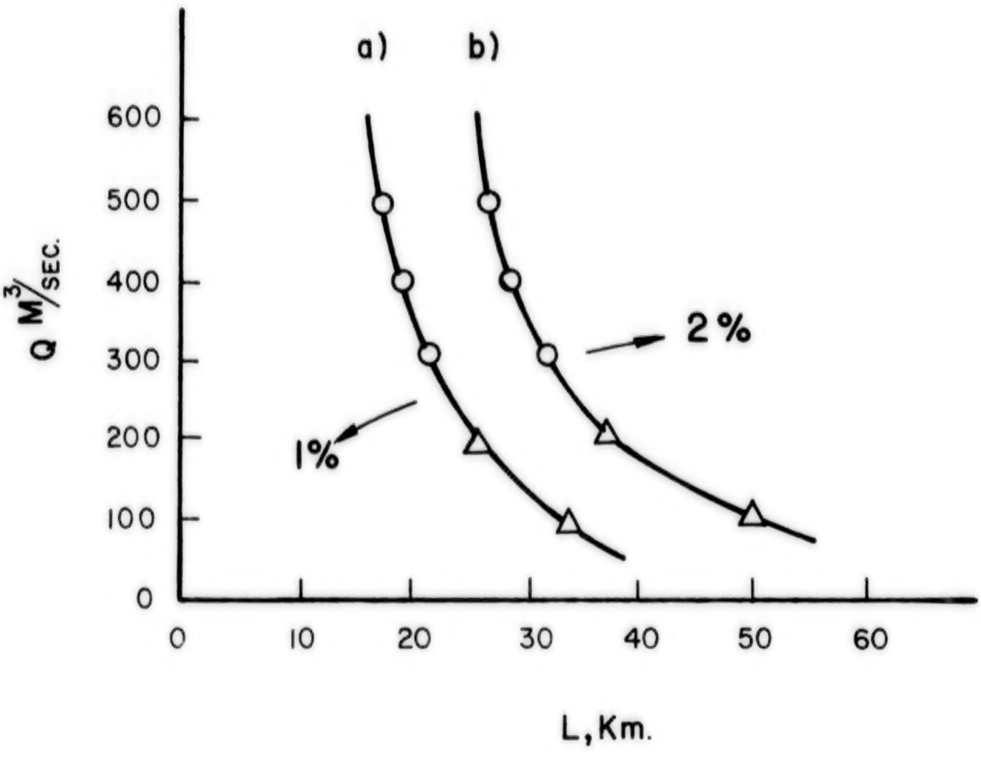


Figure 6. Dependences of the length of halocline along the principal channel of the Dnieper River on flow regulation. The initial salinity in the eastern part of the ship channel (a) 10% and (b) 15%; under these conditions salinity of the river's halocline is 1 o/oo and 2 o/oo, respectively. (Rozengurt 1974).

ship channels of the limans. The first biological indication of salt invasion into the Dniester liman was an initial reduction in distribution and catch of crayfish, a natural indicator of salinification (Meleshkin et al. 1973). A similar finding was made (1974-75) in the eastern part of the Dnieper liman. The progressive reduction of outflow from the Dnieper and Dniester decreased the size of hydrofonts almost three times (Figure 1), changing the face of these areas beyond recognition.

Millions of tons of nutrients and other organic and inorganic materials from deltas and bays stimulates biomass production (Table 2 and 6) and, in connection with climatological and hydrological factors, provides an abundance of food for pelagic and demersal fishes and benthic biota (mussels, oysters, and algae). But in the shallow zone of the Black Sea and Azov Sea basins, the structure of planktonic and benthic communities was changed under artificial flow management and biomass was reduced 19 to 30 percent and 30 to 60 percent respectively; organic material was reduced 25 to 45 percent (for the Kuban River to the Asov Sea almost 80 percent). In 1975 to 1976 the Dniester and Dnieper limans nutrients such as nitrates, phosphates, silicates, and organic detritus have decreased about 30 to 55 percent and about 90 percent of the silt load is left upstream in reservoirs.

Almost equivalent results occurred in the Azov Basin, where during 1927 to 1951 the natural outflow of nitrogen and phosphates into the sea was equal to 134,000 and 25,900 tons, respectively (almost 70 percent of which entered during the spring floods). In this same period the catch of precious fishes (pike, perch, and sturgeon) varied between 50 to 170 thousand tons annually. With water development these vital nutrients were lost to this system to about 35 to 75 percent and the areas for spawning, breeding, and fattening of precious fish have decreased about 50 to 80 percent, and the catch is now 10 times less (Osmer 1973, Dubinina 1974).

Reducing river flow resulted in increasing transparency along with decreasing turbidity and suspended sediments, and even some changes in thermal conditions. This, in turn, resulted in severe eutrophication in lagoons and in the seas and led to deficits of dissolved oxygen (Bronfman 1975, Zaitsev 1976). In addition to reduced flows the problem of sewage discharge and agricultural runoff impact on biota increased. Algae blooms and dieoff led to oxygen depletion, down to 0.2 ml/l oxygen in the bottom waters, first observed in the 1970's and extending by 1976 over an area of about 10,000 km^2 just opposite the region under the influence of the Dnieper and Dniester Bay areas (Zaitsev 1976). This eventually led to destruction of demersal fishes, millions of tons of mollusks and red algae in the northwestern part of the Black Sea. Previously, not less than 3 to 5 ml/l of oxygen was found in this area. This results from the fact that the water necessary for dilution of sewage had been decreased very much, about 30 percent. On the average, some 50 times as much water as sewage is necessary for raw sewage dilution, while only 6 to 8 times as much is necessary if good primary or secondary treatment is provided prior to discharge.

The presence of reservoirs and their dams have hindered the use of large river reaches formerly used for spawning and fattening, and the migration of egg-laying fish was disrupted. Besides, the changes of seasonal runoff abruptly changed the frequency of occurrence and duration of floods in the flood plains. For

Table 4. The salinity regime of a limited area (10,00Km^2) of the North-Western part of the Black Sea affected by the Dnieper River flow (from Rozengurt 1974).

Annual Flow (km^3) of Dnieper River:	45	30	10	5
S(^{o}/oo Cl$^-$)	6.5	7.4	8.4	9.4
Time to Establish Salinity Regime (Months)	2.4	3.6	4.8	6.0

Table 5. A probability analysis of the time to establish a new salinity (S^o/oo) balance of the Azov Sea (from Rozengurt and Altman 1974).

P	W_R(Km^3)	N(Km^3)	W_1(Km^3/yr)	W_2(Km^3/yr)	S(^{o}/oo)	t(yrs)
75	31	10,62	44,90	34,52	13,5	6,5
90	26	5,52	41,59	35,91	15,8	15,0
95	24	3,48	40,26	35,56	17,0	20,0

Note: W_R = River Flow (Km^3);
N = Computed Fresh Balance (Km^3)
W_1 = Azov Sea Outflow (Km^3/yr);
S = Salinity (^{o}/oo) and
t = Time (yrs)

Table 6. Variations of fish food resources of the Azov Sea under conditions of natural and regulated runoff (after Aldakimova 1972).

	Runoff		Azov Sea	Biomass					
				Phytoplankton		Zooplankton		Benthos	
Time Period of Runoff	Km^3	% Decrease	S^o/oo	gm/m^3	% decrease	gm/m^3	% decrease	gm/m^3	% decrease
Don River Natural	29.4	---	10.0	4.6	---	0.56	---	321*/220**	---
1952-1968	22.4	24	11.5	2.6	46	0.39	31	262/197	20
1952-1955	19.7	34	12.1	3.8	17	0.26	54	210/120	35
1956-1968	24.2	18	11.3	2.2	50	0.43	23	273/217	15
Year 2000 (Projected)	16.4	44	13.2	1.4	69	0.24	57	249	22

*Total benthic biomass.

**Preferred fish food benthos.

example, the frequency of floods in the Don Delta dropped from 84 percent to 18 percent, the size of the flooded area decreased from 95,000 to 30,000 ha, and the duration of flooding dropped from 49 to 12 days (Dubinina et al. 1974).

The reduction of runoff of about 1 km^3 during the spring spawning time for anadromous fish in the Azov Sea is decreasing the fish catch about 2,000 to 3,000 tons per generation while, at the same time, the increase in salinity of the sea of about 1 ppt from the average value is curtailing the catch about 25,000 to 30,000 tons per generation (Bronfman 1973).

As one consequence, some of the precious fishes such as sturgeons almost disappeared in the Dniester and Dneiper limans and their capture decreased about 10 to 15 times in the Black Sea basin.

In 1976, the fish-breeding plants of the Azov Basin released over 5.5 billion fry in the Azov Sea (about 50 percent of the total commercial fish husbandry of the USSR, Bronfman 1975) in order to reverse the decline of precious fish like sturgeon, pike, and perch. However, the increased concentration of young and adults in the remaining limited fattening areas (which had decreased about 80 percent) led to very sharp food competition and a deterioration of habitat space which caused the death of many of the fish.

Additional losses of up to hundreds of thousands of tons of agar weed and mollusks occurred in the shallow western part of the Black Sea in 1974-1976 due to oxygen depletion. Reduction in the primary biological productivity caused the disappearance of mackerel, pelamida, and blue fish. Although the natural stock was equal to about 100,000 to 200,000 tons, the fishing industry can now survive only on a small species of horse mackerel and the local sprat (Table 7). Some scientists have claimed that such increases in sewage, and subsequent oxygen depletion in combination with increasing salinities, will lead to irreversible effects on the remaining fisheries in the near future.

In the Azov Sea, before the 1950's, the fish harvest was equal to about 70 to 80 kg/ha. This harvest was about 6 times greater than the Caspian Sea, 8 times more than the Baltic Sea, and 25 times more than the Black Sea. The present harvest in the Azov Sea is reduced 8 to 10 fold.

Published results of exploration in other areas of the world show similar conclusive evidence of destructive changes in some deltas caused by man's activities, although these activities are sometimes considered very important for future generations.

The Nile flood waters (about 35 km^3, mid-August to December) had provided for about 125,000 tons of fishes caught from the coastal zone of the Mediterranean shelf (about 40 percent) and some brackish water lakes of the Nile Delta (about 50 percent) (Aleem 1972). In these areas, like in the shallow limans of the Black Sea and the Azov Sea basins, the increase in concentration of phosphate, nitrate, silicate, and in the growth of phytoplankton, coincided with the period of discharge of the Nile flood waters into the sea. This volume of water was almost equal to the spring flood of the Dnieper River and 1.5

and 7 times more than the spring flood of the Don and Dniester Rivers, respectively.

The capture of pelagic fish such as Sardinella changed between 10,000 to 20,000 tons; and for demersal fish, it was equal to about 29,000 tons. Such crops were due to a high concentration of primary biological productivity, detritus, and dissolved organic materials just as it was in the Black Sea and Azov Sea shelf areas.

When, for very important economic reasons, the colossal new Aswan Dam was erected on the Nile, the outflow dropped about 50 percent in 1965. As a consequence, the impact on marine life was formidable. The catch of Mediterranean Sardinella was estimated to decrease 96.4 percent (In the shallow shelf of the Black Sea and Azov Sea basins the decrease of precious fishes was similarly 92 to 96 percent; in the San Francisco Bay region striped bass decreased 35 percent). (California Dept. Water Resources Bull. 11-80) The biological and biochemical characteristics of the Nile lakes and part of the Mediterranean coastal zone changed rapidly in the absence of the natural flood inputs of nutrients and silts, and there were subsequent effects on salinity and oxygen.

DISCUSSION

There are a number of ways for preventing or limiting ecological damages resulting from extensive water withdrawals and subsequent salt invasion into shallow water zones.

First - there have been recommendations from several research institutes for enhancing the regime of limans and lagoons of the northwestern part of the Black Sea by transferring 15 to 23 km^3 (Vinogradov et al. 1971) of Danube water through a system of channels along the shore to the Dnieper liman (Figure 1). The cost of such a plan is estimated at 15 to 25 billion rubles (or 27 to 48 billion dollars). For the Azov Basin, some part of the flow of the Volga River (about 30 to 35 km^3) should be transferred. But no one knows when this should occur in the foreseeable future (Bronfman 1975). Besides, knowledge about the ecological risk of this sort of water adventure is almost nonexistent.

Second - some industrial and agricultural complexes might have their water usage restricted on the basis of excessive environmental impact. It is difficult to imagine that such an investigation and prioritizing could be done within this century, leading to some sort of agreement between users of these or other basins (for example, the San Francisco Bay Region and Southern California).

Third - to limit salt intrusion due to excessive water withdrawal by closing the straits with some type of construction such as weirs or dams. Such construction often impedes the natural movements of the bedload of silt and the migration of fishes as well as the commercial, military, and recreational traffic of man and therefore is less than satisfactory as a solution.

Fourth - to limit the water and salt exchange between bays and the seas within reasonable limits (set by nature over millenia) by limiting withdrawals to less than 50 percent of the natural runoff and by construction of a restraining channel (Figures 7 and 8).

Table 7. Catches of precious and rough fishes in the Northwestern part of the Black Sea. (from Zemlianski 1975).

years Catch (Tons)	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Precious Fish (valuable)	2,793	2,976	4,741	3,146	1,752	1,720	933	1,160	928	622
Rough Fish (non-valuable)	11,382	12,284	12,188	12,699	9,388	12,707	7,878	12,385	14,047	16,269

Caption for Figure 7.

a. Dependence W_2 Km^3 (the sea inflow) from the length of channel under different elevations (ΔH) of the system on the Dniester Liman-Sea.

b. Dependence W_1 Km^3 (the Liman outflow) and W_2 Km^3 from the length of channel under different elevations of the system on the Dnieper Liman-Sea.

c. The changes of length of the Dniester Liman restraining channel for different volume of flow (Q m^3/sec). Depth (speed U m/sec) of channel is about 6 meters. B - the width of channel.

$\Delta H = H_{Liman} - H_{sea}$ 0.1 meter (difference of elevation). 1 - channel with natural

roughness, 2-4 channels with forced artificial roughness (concrete with height = 1m., there density of distribution on the bottom is equal 20, 10 and 5m, respectively). Under persistent reducing of outflow about 40-50%, the channel should have B = 50m, L = 330m or B = 100m, L = 1600m, the density of location of concrete 10m, under natural roughness of the length of the channel as much as 1.75 times.

Figure 7

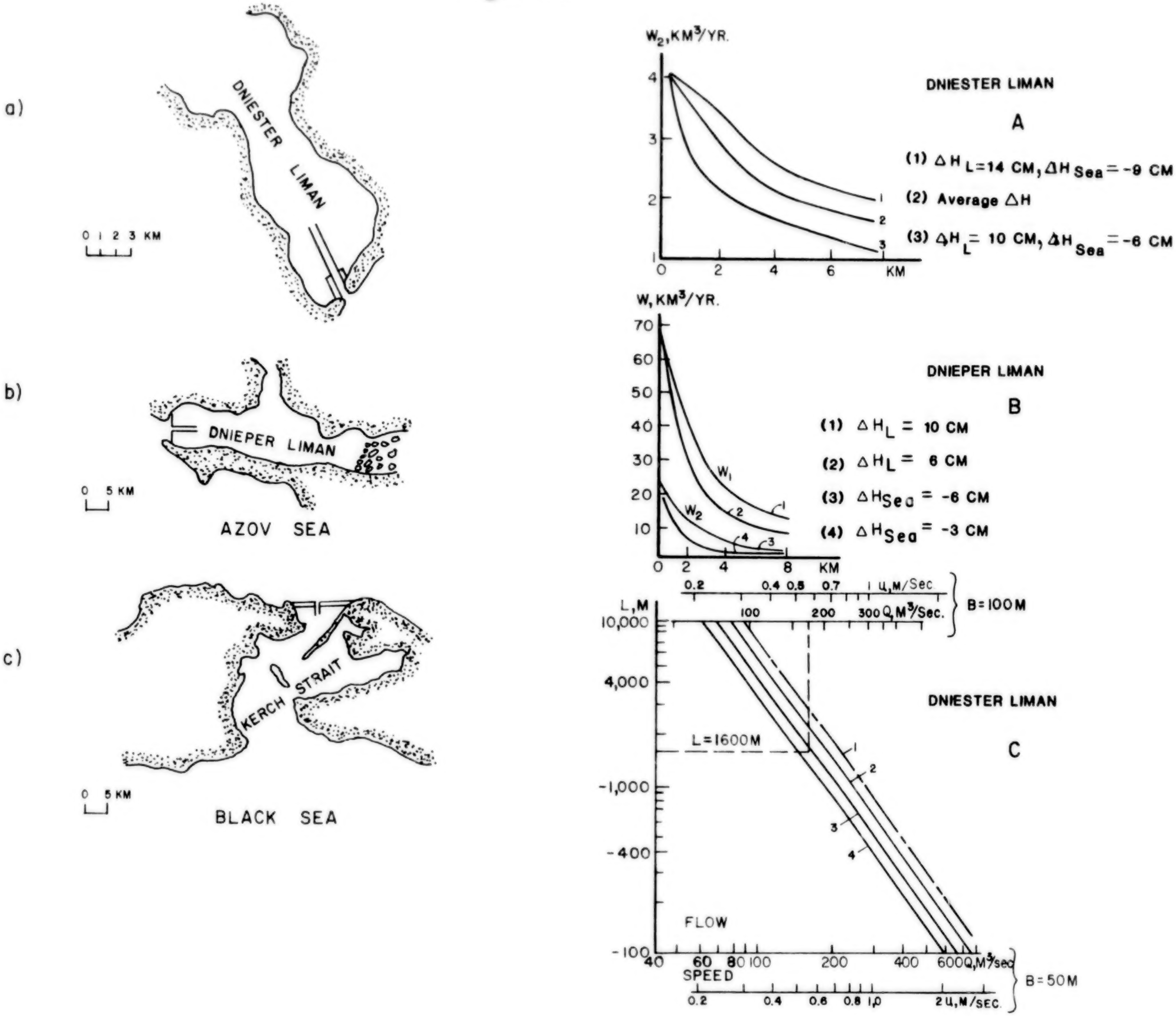
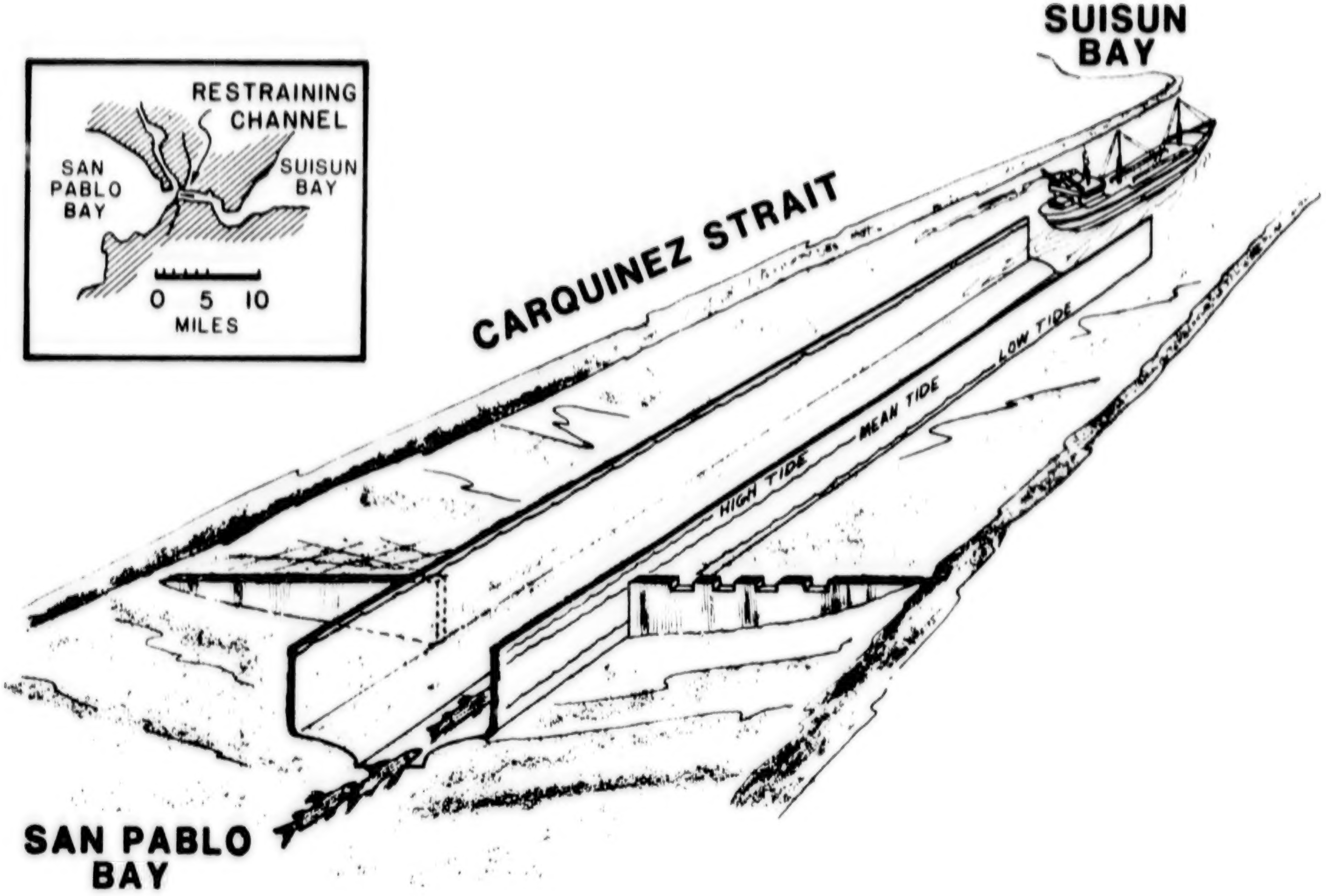

a)
DNIESTER LIMAN
0 1 2 3 KM
b)
DNIEPER LIMAN
0 5 KM
AZOV SEA
c)
KERCH STRAIT
0 5 KM
BLACK SEA
W_2, KM³/YR.
DNIESTER LIMAN
A
(1) ΔH L=14 CM, ΔH Sea = -9 CM
(2) Average ΔH
(3) ΔH L = 10 CM, ΔH Sea = -6 CM
KM
W, KM³/YR.
DNIEPER LIMAN
B
(1) ΔH L = 10 CM
(2) ΔH L = 6 CM
(3) ΔH Sea = -6 CM
(4) ΔH Sea = -3 CM
W_1
W_2
KM
u, M/Sec
Q, M³/Sec.
B = 100M
L, M
DNIESTER LIMAN
C
L=1600M
FLOW
Q, M³/sec
SPEED
u, M/SEC.
B = 50M

Figure 8



SALINITY RESTRAINING CHANNEL

Figure 8. Schematic of a proposed restraining channel to control salinity intrusion into the San Francisco Bay-Delta. Channel length is about 1.5-4 Km, depth 12.5-13.5 M, and width 200-250 M. Weirs of 250 M each close off the rest of the strait at low tide.

Figure 9

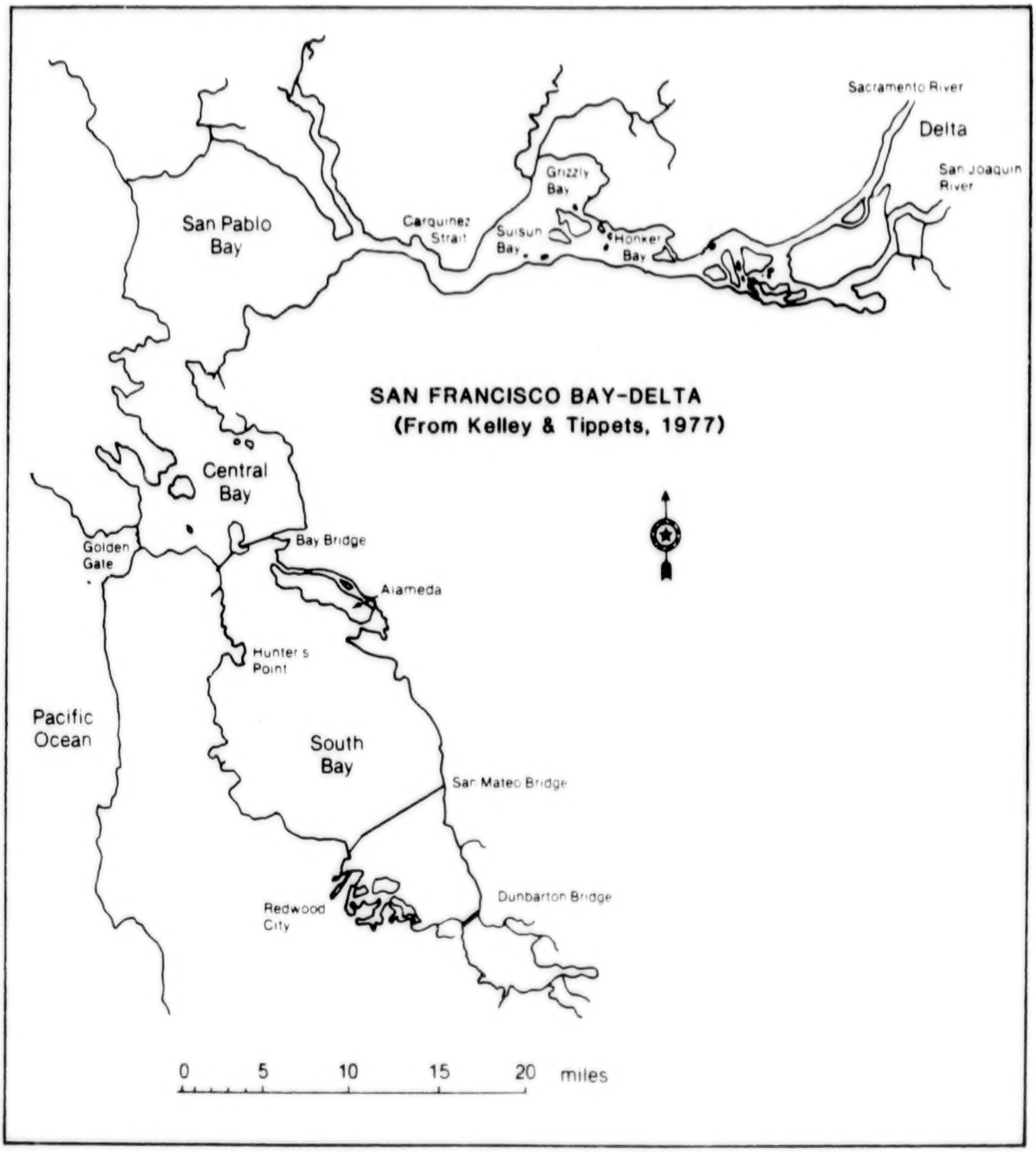


Figure 9. Location map of the San Francisco Bay - Delta.

Caption for Figure 10.

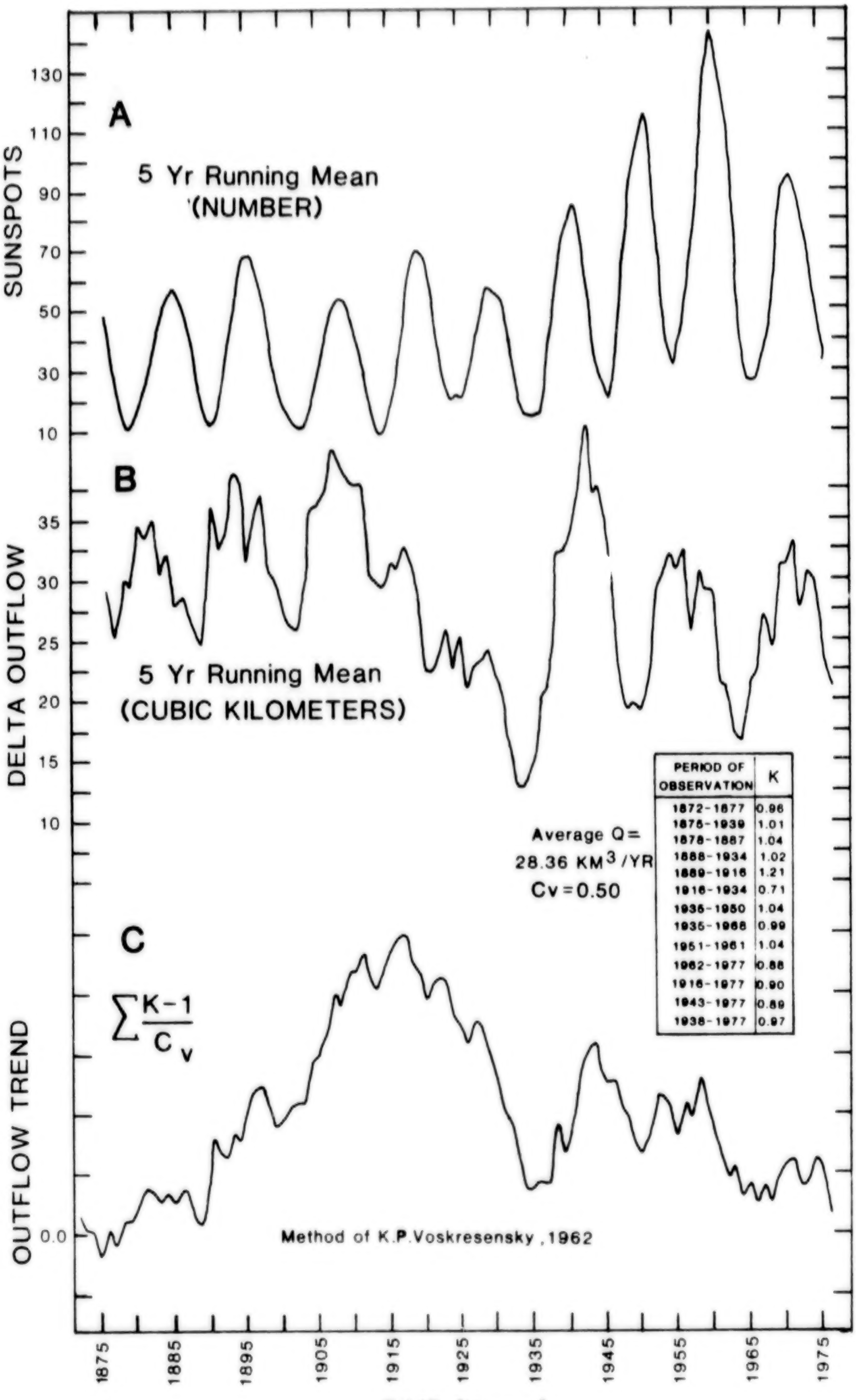
The Sacramento-San Joaquin Delta.

A. Fluctuation of sunspots number (Wilson Observatory, So. Cal.), 5-year running mean, 1872-1977;

B. Sacramento-San Joaquin River outflow, 5-year running mean, (1872-1921, Sacramento River, Cal. DWR. Bull, 26; 1922-1977, both Kelley and Tippits, 1977); and

C. Differential integral normalized curve of modulus of delta outflow, 1872-1977 (from a table of variations of K there are two complete cycles of water content: 1875-1934 and 1935-1968; the driest period is 1916-1934; the wettest is 1889-1916; the last 15 years is a dry period.

Figure 10



PERIOD OF OBSERVATION	K
1872-1877	0.96
1876-1939	1.01
1878-1887	1.04
1888-1934	1.02
1889-1916	1.21
1916-1934	0.71
1936-1950	1.04
1935-1968	0.99
1951-1961	1.04
1962-1977	0.88
1916-1977	0.90
1943-1977	0.89
1938-1977	0.97

An actual model (about 42 square meters in size for the Dniester River liman, the pre-strait area of the sea) was built by the Institute of Hydrodynamics of the Academy of Science of the Ukranian SSR, Kiev, in 1974 on the basis of this idea (Rozengurt 1969, 1974).

Computations of water exchange in natural conditions and under a regulated strait have shown the sophisticated effect of decreasing salt exchange between various waters can be achieved by application of dams or weirs with navigable canals (Rozengurt 1969, 1975; Rozengurt et al. 1978). The regulation of water and salt exchange is ensured by the width and length of the navigable canal and some additional construction (barages on the bottom, special diaphrams, etc.) which can decrease the necessary length of canal without suffering further salt intrusion and even under regulated flow reduce 50 percent of natural kill.

The proposed method of water exchange regulation does not disturb the ways of fish migration and the movement of river load, which have been forming for ages, and it preserves the transportation connections between basins. It has been considered practical for the Dnieper liman and in the Kerch Strait of the Azov Sea (See Figure 7).

Direct experience and the published results of the effects of water development abroad, all point to the inescapable conclusion that no more than 25 to 30 percent of the natural outflow can be diverted without disastrous ecological consequences ensuing. The early warning signs of excessive withdrawl are apparent in the reduced productivity of fish and wildlife resources, changed biological structure of plankton, benthos, and fish communities, increased salinity intrusion affecting municipal and agricultural water supplies and the biota, and increased effects of pollution loads in progressively more stagnant waters.

The above experience is directly pertinent to similar problems faced today in the San Francisco Bay-Delta of Central California shown in Figure 9 (Conomos 1979). The historical, average annual Sacramento-San Joaquin River delta outflow tributary to the bay was 38 km^3 (1871-1929) and is presently only 19 km^3, a 50 percent reduction. A similar or even greater reduction occurred in the past and led to very serious effects even prior to major water developments. As a consequence of present variations of flow, including recent critical dry years such 1976-1977, there have been measured increases in salinity of 6 to 10 fold in the delta, 2 to 4 fold and 2 to 3 fold in Suisun and San Pablo bays, respectively, during some seasons and years. If the volume of river runoff is decreased to a level of 75 percent of the long-term average, the salinity in Suisun Bay will reach, especially in summer, almost the value of salinity of the San Pablo Bay in 2 to 4 years, which will cause the death of fresh and slightly brackish flora and fauna, and will ultimately destroy all irrigation and municipal systems fed by the delta. This expectation should be kept in mind when considering the eventual projections of 75 percent water withdrawals from the San Francisco Bay-Delta in the year 1990 (Kelly and Tippets 1977).

It is even more important to point out that the above predictions are based on historical patterns of available runoff and that the choice of an appropriate "average" timeframe is crucial to the success of such projections. A more recent analysis of Sacramento River run-off extending further back in the time (to 1872) and using different methods shows that there is a persistent trend of decreasing runoff in this basin from natural causes (Figure 10).

Thus, maintaining the San Francisco Bay-Delta system in a near-natural state requires detailed study under a variety of outflow conditions along with special considerations of often neglected topographic, oceangraphic, and meteorologic factors.

In summary, the first priority of such work should be to indicate what limits there are to freshwater withdrawals which will not cause irreversible ecological changes throughout the region from the delta to the coastal zone. The second priority would be to make strictly scientific explorations regarding salt regime from the ocean to the city of Hood (near Sacramento) in order to assure that freshwater irrigation systems, even above the delta, are not damaged forever by salt intrusion. Third, it is necessary to assess and determine the total potential assimilative capacity of the delta, Susuin Bay and San Pablo Bay, and the rest of the San Francisco Bay area, to discharge of present and future municipal and industrial pollutants and agricultural drainage waters. This is a vital need from the standpoint of the self-purification of the bay. Bay sediments and the three kilometers of the bay water body are exposed to a variety of point and non-point sources of pollutants which are transferred by runoff. Finally, all the above actions are necessary to make a real prognosis for future water withdrawals deemed necessary to sustain agricultural and municipal needs along with necessary fishery and recreational requirements. Consideration should be given now to construction of a dam with a built-in restraining canal, ensuring constant connection with the sea but limiting the entrance of seawater to an amount which not only preserves the acceptable salinity conditions but also facilitates the future freshening of bays, creating conditions for free navigation and transport without sluices and for fish migration without fish ladders.

Basic schemes of water development should consider first the needs of nature and be based on a scientific, not political, assessment of the real volume of water available in excess of nature's needs. All construction should be predicated on its ability to assist nature's way, not to block it.

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FINAL PLENARY SESSION

John Clark

Conservation Foundation
Washington, D.C.

FINAL PLENARY SESSION

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Conservation Foundation
Washington, D.C.

This is your session and I'm going to be as brief as I can, taking just a few minutes to emphasize several points. Then we want to spend as much time as we can trying to refine our approach, our thrust, and to define more precisely what we are trying to do. I'm going to start this off, but we can throw out all the recommendations and write new ones if you want. My conclusions will be very simple, perhaps disappointingly simple to many of you, but it's time for simplicity if we are going to get our message across.

Today we will talk about the potential for the future. We want to talk about things that will help all of us accomplish the things we desire and need. We won't be talking about specific recommendations for kinds of research or data bases or specific interagency problems. Those can be discussed after we finish with the big problems, but first we need to do something quite imaginative and quite large in scale to try to improve the situation in a national sense.

The subject is freshwater flow into estuaries; the amount, the rate, and, to an extent, the quality of the flow. We explored the whole state of the data base for estuaries and broadened our discussions to include a number of key topics besides just the amount of water flowing in. We agreed that estuaries are exceedingly productive and valuable to coastal communities and to the Nation as a whole, but we all perceived that estuaries are a commons and are suffering the neglect so typical of common resources. Estuaries, too often, are the vacant lot in the coastal neighborhood. Even so, most of us here have dedicated some of our energies to conserving estuarine resources.

Many of us are cynical about the estuarine conservation task. We seem to have a rightful cause, but we seem to be losing ground. Somehow, the new laws of the late 1960's and 1970's CZM, EP, Clean Water Act, Endangered Species; all taken together still have not provided what we need. We simply do not have a mandate to conserve the estuaries of this Nation.

Many of us thought we had the mandate in the 1960's. We expected a bill of rights for estuaries before the end of that decade, but it slipped away from us. Then we hoped something could be patched up from the new laws of the 1970's. But it has not worked.

After having said all that, I want to assure you that I am among the cynics. We do have a good cause and we can succeed. We can get a lot of help from the conservation groups. We can get the attention of Congress. We can get the attention of the White House, if we do it right. We can get the mandate, the standing for estuaries. We won't save every fish or every bay, but we can win a lot more than we lose.

We have a good start right here and things like this have happened before. In 1972, at Woods Hole, about 90 of us, including some of the people in this room, gathered to decide what could be done about the very complex and confusing job of conserving the coast. That meeting had a very pronounced effect on what has happened in the last eight years. In 1976, in Annapolis, we recognized that there was a problem with barrier islands. Since 1976, barrier islands have been recognized as important resources, leading to executive orders which have become legislation.

There is a bill, now being considered in Congress, to protect estuaries. For those of you who do not feel as enthusiastic as I do, who doubt that this meeting will accomplish anything, I've been asked by Tom Linton to remind you of something out of history that I think is very pertinent. It was in 1858 when Darwin read his first paper to the Royal Society on the evolution of species. In the annual report for 1858, the President of the Society wrote"... this year has not been marked by any of those striking discoveries which at once revolutionized, so to speak, the department of science on which they bore." So, sometimes, the forest is not visible or is obliterated by the trees. We really have made a major accomplishment in pushing the state of our knowledge to the limits. Now, we are ready to consider what we really want to recommend. First, just to clarify things, I would like to read a bit of doctrine that was put down for a particular estuary which I will call Flat Fish Bay, just so we don't stub our intellectual toes on a particular issue. Here's what it says: "The natural resource that is perhaps most critical to maintain the integrity of the bay ecosystem is fresh water. Both the quantity and quality of the fresh water entering the bay drastically affects various characteristics of the water such as salinity, oxygen levels, nutrient content, and temperature which in turn influences the organisms in the water. Any deterioration in the flow of fresh water into the bay would result in a change in the natural components of the bay ecosystem and thereby in a change of recreational and commercial potential." Then we read: "In many ways, Flat Fish Bay is typical of coastal bay regions with shallow bays, estuaries, and marshes sheltered from the open gulf by barrier islands and peninsulas. In other ways, however, it is unique; the particular combination of interacting biological, chemical, and physical features make this bay area unlike any other. It is this combination of typical and unique ecological features that gives Flat Fish Bay its distinctive character. Its natural resources provide abundant recreational and commercial opportunities."

Now from those passages, note first that the author stresses the high values of estuaries that we all recognize. Second, the author identified important individual ecological factors that have to be controlled within this area. The author stresses that we are dealing with an ecosystem. This is a system, with complex parts and a very complex process. And third, the author both emphasizes that it is a typical estuary and at the same time persuades us that it is unique. Let me read again: "Flat Fish Bay area is typical of coastal bay regions. This bay has a combination of typical and unique ecological features. It is typical of estuaries and unlike any other."

This ambivalence is important. Each bay is distinct and yet together they form recognizable, highly valued resources. We may speak of typical estauries at the same time we're saying each one is unique.

This point brings us to my central point. I am going to lay out five different recommendations which logically follow from the discussions we have had and from my little build up here.

First, we must deal with estuaries as complex ecosystems. They are not just basins of water, isolated from other parts of nature. They are ecosystems, and we have to know about structure and processes before we can manage the system.

Second, and most important, we need a national mandate for estuaries as high value resource. Estuaries are a class of resources, something we can recognize as having common attributes and common values wherever they appear around the coast. This recognition is essential before we can talk about a national program for estuaries. But we do not think we can prescribe nationwide or even regionwide standards for estuaries.

Third, we believe that each estuary has to be treated as a unique resource, an ecosystem with its own separate management plan. But, this has to be more than a vague national goal. There has to be a conservation objective, stated in clear and simple terms, which politicians, fishermen, and engineers can visualize. It must be an objective that forms the target for governing water inflow to estuaries.

Fourth, we propose that this conservation objective be the maintenance of an optimal salinity regime for each estuary. We would recognize maintenance of an optimal salinity regime as the overall guiding objective for management. Everybody can understand what salinity is, and everybody can taste water. Politicians can deal with it. Engineers can deal with it. Fishermen live by it. It is a distinct central focus for management. Oversimplification? Sure. But now we are talking about a political thrust. It has to be simple. Given that, we can fit the other pieces and parts, and needs and necessities in with it. The estuarine salinity regime should be, if I correctly interpret what I have heard in the last three days, as natural as possible. With the salinity regime maintained in its natural state, the natural structure and processes of the ecosystem should be maintained. I think we would all relax comfortably if we thought that all the estuaries in the nation could maintain their natural salinity levels and the natural spatial and temporal variation of these levels throughout the containment basin. This can be achieved in some estuaries, like Apalachicola, where we have a lot of control, but we are going to have to settle for something less in a good many estuaries.

In this context, we need to talk a moment about conserving a function. In other words, control of the salinity regime will conserve the functions that produce the values we wish to protect. To preserve the function, we must set limits and decide water budgets and water schedules. Where we have to compromise, we will have to settle for less. Our target cannot be the full national solution that we would all like to have. We have to limit our objective to conservation of the function of the estuary. We will then be managing process and structure by addressing function. Salinity will enable us to deal at the ecosystem level, where this whole issue belongs. At the minimum, we believe that every water project should be required to address estuary and freshwater needs as it is planned. In other words, we want an estuarine impact assessment for every major water project in this county. We want people to be conscious of the problem, to be required to state what effect their project will have on estuaries. If they can deal with the complexity of the whole impact, they certainly can talk about what will happen to the salinity regime and from that we can make a lot of interpretations.

Last, we propose that this conference go on record concerning the preceding four points, properly elaborated and qualified, and that we vigorously pursue these recommendations with conservation organizations, governmental agencies, the Congress, and elsewhere. Those of us who are in a position to do so should vigorously pursue these recommendations. We recommend that we start the pressure now and watch for the breakthrough opportunity which I feel sure will come within the next few years. That is our platform and I would like to hear what you have to say about it after I invite my colleagues of last night to comment on my remarks.

Gilbert Radonski, Sports Fisheries Institute: I think John Clark summed up everything quite eloquently, especially with respect to separating the biological from the political aspects of this problem. During the past three days I have heard some excellent presentations on things we have always taken for granted. But they were clearly restated and the many exceptions to accepted simple processes were elaborated on.

People like John Clark and myself are going to have to rely on field scientists to continue to bring forth these problems. Then we are going to have to somehow move in the political scene, to express these things in ways that cause the whole country to share the same values. John was absolutely correct Tuesday when he said that the further you get away from the estuary the less interest there is in it. It is up to us to take the proceedings of this important conference and put them into a simple document that people can understand and convince the politicians that when they do build a dam upstream, out of sight of the estuary, it does have an impact. I think that this conference will go down as being very important as the first step to accomplishing many things that have to be done.

Norm Benson, U.S. Fish and Wildlife Service: I'm not going to read all the comments and recommendations that were presented to me. They are very good and will be included in a summary paper which will also include the remarks that John made. So, if you expressed some concerns or recommendations, don't feel that they will not be considered. But we felt that we had to focus on a few major recommendations which enveloped all the more specific ones.

Rezneat Darnell, Texas A&M University: There is one thing missing from this conference and that is as follows: estuaries are now being managed largely by a number of different agencies, each with its own specific guidelines, its own specific aims, and its own authorizations. There is no central authority for the management of estuaries. Somehow or other, we have to give some thought to the question: who should be the managers of estuaries? Somebody must take the lead in management. Otherwise, solutions will be almost impossible because nobody will have estuarine management as a central priority.

John Clark: I think that is a good point. We should note that we are doing a fairly good job in the wetlands, at least those on the major water bodies and the coast. There is no office or bureau of wetlands anywhere, yet somehow, by a little legislative and administrative magic, we're doing a fairly good job. We may have to settle for something like that for estuaries.

Rezneat Darnell: I'm not saying we necessarily should be identifying the manager, but I think we should identify to whom we are addressing our concerns, whether the Corps of Engineers, the Fish and Wildlife Service, or some other group. Let's identify the organizations which have a role to play and if there is one which can take the lead, then identify that one.

John Clark: I think that's a good idea. We certainly can't trust to luck that the message will arrive in the right hands to get the action we need.

Mr. Clark invited comments from the floor. These comments have been transcribed from a tape recording of the session and have been edited for grammar and clarity. Whenever possible, speakers have been credited with their remarks. Any speaker who did not divulge their identity has been named "Anonymous."

DISCUSSION

Anonymous: I think that we need a water management plan for each estuary and its watershed in the United States. I know we cannot just start out and do that for every estuary, but we could start with the primary estuaries, proceed to the most threatened estuaries, and gradually work our way through the remainder. I really think our management plan must include not only the estuary but its watershed, for a large number of reasons brought out in this conference.

John Clark: Do you have any idea what sort of form that might take, or who would authorize or fund it?

Anonymous: Not really. I would think that the Water Management Council could play some major role and I would also hope that the Fish and Wildlife Service and the National Marine Fishery Service would be involved.

John Clark: Thank you. Ben Mieremet suggested that the special area management program being prepared by the Coastal Zone Management Office may be helpful in this type of planning. Some states, Washington, for example, certainly could do it. Other states, such as California, could get a grip on some if not all the watershed and some of the estuaries through their coastal zone management program. Your suggestion is helpful, but I think we need something that is even bolder and directly tackles the watershed management issue. I'll give you just a clue of what we're considering for the Apalachicola National Estuarine Sanctuary in the Florida Panhandle. That sanctuary is serving as a test case for many of these ideas. We're hoping to establish a kind of Fish and Wildlife Coordination Act right to review any major projects in the watershed by the estuary management committee. That watershed is 18,000 square miles of Alabama, Georgia, and Florida and we would like the right to review the major projects that could significantly affect the estuary. Certainly, the Fish and Wildlife Coordination Act review mechanism has accomplished a lot in the last 15 years, especially with public support. The Apalachicola case would be a good start and a good example. It illustrates our need for a mechanism larger than states because so many watersheds go through many states.

Keith Bayha, U.S. Fish and Wildlife Service: In marketing the results of this symposium, one arena that might be considered is the U.S. Water Resources Council. Many of you may be aware that a new mandate is currently being considered in the Congress in the form of an amendment to the 1963 Water Resources Planning Act. It could be that a section could be written into that legislation to accomplish what John just described. This could be added to the independent review function that was discussed on opening day.

John Clark: I'd be very happy to take that up with Jerry Seinwell if that seems like the right approach or if anybody else is willing to do it. He has already said he would like to cooperate.

Anonymous: John, I have two concerns about the recommendation. First, the emphasis on salinity regimes sounds a little like we are trying to hold the system in a state of nonchange. It is very important that we make the statement clearly indicate that the salinity regime must be considered in a broader sense than the one that presently exists.

Second, I think there should be a specific recommendation concerning maintenance of the transported sediment, both suspended load and dissolved solids, input into the estuary system. We heard from the Corps of Engineers, for example, that during the last 20 years there has been something like a 50 percent reduction in transported sediment load coming down the Mississippi River, which I consider a very important fact.

John Clark: Let me comment on the second point first. I'm struck by the fact that on the Mississippi you are starving for sediment while I'm working at a bay in South Carolina where sediment is the abomination of the place. It's ruining the economic future of Georgetown, South Carolina, and upsetting everybody's environmental, social, and economic plans and we would like to find a way to through-put the sediment to the ocean as fast as possible. So I don't think it goes in one direction, but the subject is one that definitely should be addressed.

Now, on the first topic, I very carefully did not say maintain salinity. I very carefully said maintain the salinity regime. When I talk about qualifications to the recommendation, I mean that we should emphasize the need for sensitivity to seasonal needs. For example, oysters spawn by temperature triggering. They need fresh water when it is coming naturally and not sometime in, say, February. That has to be considered and it does make the matter complicated. Somebody has to do some serious study of the functional elements of an estuary before the estuarine impact assessment can be effectively made. We have to know the regime in detail in order to maintain it. Is that the essence of what you are saying?

Anonymous: I was thinking in terms of longer time periods; the gradual changes in salinity regime which might drive an ecological succession over a period of a century or more, for example.

John Clark: That's big time stuff. I think it is well put and we will include it.

Anonymous: I have two questions. First, what are your reactions to the bill which is attempting to develop a board for coordinating estuarine research in Chesapeake Bay? Second, can an interstate river-type commission be created as a legal entity to deal with estuarine areas? Or, could we create in interstate-like commission for San Francisco Bay even though it is not in more than one state? Could a body comparable to an interstate river commission function as the governing body for an estuary?

John Clark: Your second question has been pretty well debated around the Chesapeake Bay. On your first question, there have been serious problems in the Chesapeake Bay about trying to focus research on management-specific topics and trying to get a good management data bank. Most of us are discouraged over the way that the budget is being spent. A lot of good work has been done but minimal management recommendations have resulted from the work.

Actually, the Chesapeake Bay is not an estuary at all. It is a series of twelve estuaries all feeding into a common water basin and real progress on the Chesapeake Bay will happen only when we stop talking about the bay as a whole entity and begin to look at these separate but interacting ecosystems that are formed by the basins and waters of each of the rivers. As far as what the pending legislation could do, I think all of us would appreciate anything that Congress is willing to do to help us focus research to provide managers with what they need. I think the fault is on both sides. Scientists have not been responsible about trying to address their research projects to management needs. But managers have not been thinking through what kind of data they really need to make next month's or next year's decisions.

As far as the details of the bill, the idea of a river basin commission for the Chesapeake Bay has not won much favor, because people have a very stylized idea of what a river basin commission does. However, I think that when we get some solid estuarine policy, existing river basin commissions will be a good place to take it because the commissions tend to look more broadly at problems than do individual project advocates.

Jim Anderson, U.S. Fish and Wildlife Service: We heard quite a lot about the need for freshwater inflow and maintaining the right salinity regime. Is there anything in those recommendations about looking at the water quality as well as quantity? We have encountered some real problems in the last couple of years in Nueces Bay and some of the other Texas bays.

John Clark: Water quality management is really conducted in two ways in the United States today. One is source control, mostly point sources, where we try to get management practices at the source which will reduce pollution input. Supposedly we are dedicated to the goal of totally eliminating pollution. The other method is to look at the water basins themselves and, if quality has deteriorated below a certain threshold, we are supposed to exercise particularly stringent controls on pollution. We are supposed to make sure that there is no further deterioration of any of the water bodies in the country. Neither approach really puts together a plan for a unit resource. In fact, EPA does not even think about that. EPA is tuned to the concept of the quality of human life that arose about ten years ago. That is what they are protecting and taking care of, which is not the resource business at all. Now, do you have any idea how one could state water quality objectives for an estuary?

Jim Anderson: I think we need to look more at the health of the fish and wildlife resources than concentrating so much on human health, as EPA does. There needs to be some kind of a coordinating body to do that because, as you mentioned, EPA does not consider the cumulative impacts when they grant permits. They are looking at one specific source each time.

John Clark: The management plan, as well as asking for a certain amount of freshwater inflow to establish a certain salinity regime probably ought to require a water quality plan as well. I wonder if anybody here can think of a way to express that objective. One might say that you would have a water quality plan for each estuary which would maintain the ecosystem at some optimal level. Does anybody have any ideas on how we can express water quality objectives?

Dan Tabber, U.S. Fish and Wildlife Service: We could probably strengthen our platform by including a seconding of the existing nonstructural controls which regulate development on estuaries. I would also like to suggest that we recommend to Congress additional or more effective institutional non-structural measures such as aquisition, zoning, and a more effective permitting process. In Louisiana and Mississippi and, probably, in most other areas of the country, the most pressing need is the fact that if we do not do this we may lose some estuaries before we can implement these water-management plans.

John Clark: That is a really good point and one that several people have mentioned in the recommendation which we have received. You do need some kind of action which involves the local governments and municipalities that lie around these estuaries. Only governments possess zoning and other regulatory powers, which could be very helpful. The recommendations also do not stress the need for acquisition of critical surrounding areas, but I think that goes without mention. What I think is implicit is the continuing search for ways to conserve without purchasing in fee any more land than we have to. We are under attack by many groups who really do not want anyone coming in and buying up parcels of floodplain, wetland, rangeland, or whatever. So, we have to think about more innovative approaches in gaining control over the land than buying the deed.

Dan Tabber: In our area, it has been left up to the state, or the county or parish, and it has not been, by and large, successful. I realize that sometimes local entities do not want Federal intervention but the state is the minimum unit in our area. I know in other areas around the Southeast, particularly Georgia, they have been very effective.

John Clark: When we created our plan to designate Apalachicola Bay and the Apalachicola River to the head of tide as a sanctuary, we drew up plans to purchase more wetland, incorporate already purchased areas, and purchase some adjacent lands and floodplains. Then we realized we had only pushed the boundary back a little and that beyond the new boundary was the spector of bad use of private lands. So the next thing we did was to get the county commission to go ahead and fund a local land use planning effort in which they are going to adjust their zoning and building codes to provide the buffer area in the private land around the designated sanctuary. I suppose once that is done, we will find that it creates another boundary beyond which we need to do something, ad infinitum, until we arrive in Atlanta, Georgia.

Donald Williams, University of Southern Mississippi: As I listened to papers this morning and the comments here, I kept thinking that there is a critical question as to what regime we want to conserve. Should it be the already highly modified, highly polluted, over-sediment-loaded input that is coming in, or one that may have existed in the past? Do we just hang on or do we actually try to improve the resource?

John Clark: I, for one, think it is time that restoration entered more strongly into our lexicon and that we tuned more of our research objectives and efforts toward restoration. I'm working on a little estuarine restoration project up in North Carolina. There, we are trying to restore the hydrologic processes that have been lost by bridge construction and the Intercoastal Waterway. I have talked to other people and it seems that there is a growing realization through the country that, as we begin to make some headway on wetlands, dredge and fill, point source, and some of the other things, we are now getting to the point where restoration should be a very hot item. One way it can be done is illustrated by a project on Long Island. There the estuarine wetland system was restored as mitigation of a bridge building project which had damaged the wetlands by blockage and excessively small culverts, among other things. In time, we are going to do more restoration. The problem with restoration is, who is going to pay for it? When we are dealing with permits or the effects of construction projects, somebody has already put up the money, the Federal Government, private developer or whoever. They are aggressively trying to pursue this project and spend their money. To ask them to spend a little more for environmental protection is one thing, but to advocate that a certain bay be dredged out or the marshes be replanted, or sea grass be started, or causeways that are interfering with circulation be torn out, all those things are de novo expense. This leads to the idea that we need to have our restoration objectives in mind at all times and then hook them on to mitigation wherever we can. There is a corollary to that. If you are going to try to work with a salinity objective, you may crank it back to some place in time where you believe that your minimal functions produce the values you want.

Tom Yokum, National Marine Fisheries Service: You asked about a definition for water quality. In the present reauthorization process for the California Central Valley Project, they have used a quick and dirty definition which specifies water quality in terms of conditions that would maintain fish and wildlife at some recent historical level.

There are some problems with that approach, but it is a quick way to provide something that a politician can understand.

With regard to the four recommendations, initially when you said salinity regime, I sort of blanched. In the San Francisco Bay estuary we keep redefining the estuary as it moves on up the Sacramento River. If we want a salinity regime, we will have to define the area where we want the salinity regime to be maintained. There will be a salinity regime somewhere, perhaps in San Franciso Bay, maybe in the delta, and maybe moving its way up toward Mount Shasta.

John Clark: If you just think of an estuary as a kind of narrowing bay structure, narrowing from the sides and often from the bottom, the more you move it back the less estuary exists. The volume decreases exponentially as you move toward the head of the estuary, so moving the interface ten miles upstream may be reducing the effective size of the estuary by 90 percent.

Tom Yokum: Estuarine impact assessment for major water projects is something we have been pushing for in California. In addition, we need to look at cumulative impacts and not just the impact of any one project. Estuaries are being piecemealed to death so asking for an assessment of an individual project does not help much.

I was hoping that this symposium would say something about interim standards. We need to maintain flexibility and maintain enough water in the system so that we can meet the goals whenever we figure out exactly what those goals are. Mike Rosengurt said that reduction of river flow by more than thirty percent represents ecological problems in the Soviet Union. If we could get a symposium to at least say some percentage of river flow means estuarine trouble, it would give those of us on the management end something we could refer to rather than saying this is what we think. Then, when I am asked for evidence, I can say John Clark says so and maybe that will be sufficient.

John Clark: Before I respond to your point, let me say that the next major conference on estuaries will probably have to include more of the management, legal, institutional, and political structure. We have probably gotten as far as we can talking to ourselves as technicians. The next step is to meet the other groups and to discuss this with people who supposedly know how to get things done.

There is some potential for the states to improve how they are managing estuaries through their own means and by cooperation with local governments. But, from the California perspective, how about some change of focus or policy at the national level? How could that help California to do its job better?

Tom Yokum: I don't know. The California water rights picture is extremely confused. My own opinion is that there is not enough water left in the system now and I do not know how you get it back. There is going to be considerably less water in the system in the next 20 years irrespective of any recommendations I make.

Anonymous: As a non-technician, I think it is safe for me to suggest that the other side of the salinity regime question is the amount of fresh water coming in. Using what I decided to call the Rosengurt ratio, I would suggest that reduction below twenty-five percent of the normal freshwater flow is trouble. Mike Rosengurt told us about that on the rivers in Russia. He used twenty-five percent because the freshwater flow naturally fluctuates that much. When you remove up to thirty percent, you are beginning to enter the hazard area. Then you hit thirty-five percent and trouble. The rivers entering San Francisco Bay right now have somewhere between sixty and seventy percent removal, so you can see what kind of trouble we are in. As you seek a definition of the salinity regime, perhaps it would be useful for you to put some numbers in it. Or, perhaps, that is for the next conference.

John Clark: I agree that we are going to have to do more than just talk about inflow rates. When we have another one of these symposia, we ought to have somebody prepared in advance to look at the data base that we have and see if we can either confirm that number for the United States or come up with some other number that is more appropriate. Twenty-five percent may be the number, but we ought to confirm it. If we came prepared, if someone had really done the research on it, then we could thrash it around and come out with something that would be very helpful. We certainly do need guidelines.

Wiley Kitchens, U.S. Fish and Wildlife Service. I would like to express my concern regarding the salinity regime recommendation. You made a point earlier that estuaries are individual entities. I don't think that, for example, dilution water is the answer to the problem in coastal Louisiana. We need to separate the issues here. Sediment starvation, in my opinion, is the key problem in this particular part of the coast. The river continues its discharge. If you don't believe that, take a look at some of the Landsat imagery. It is a matter of where the fresh water and sediment load are being discharged. I, for one, think that salinity is just as much a variable issue in the maintenance of estuaries systems as is the sediment budget. Maybe the real issue is the hydrologic regime and the factors attended to that particular system.

John Clark: Thanks. Yours is the seventh contribution that I've added to expand and develop on my original list. Maintenance of the hydrological regime is where we need to head. We need to be able, though, to simplify the objective to whatever will get the idea across in the simplest way possible. Consider the combination of salinity, water flow, and sediment transport. None of these are so scientifically complex that laymen cannot grasp them. We are approaching the point where we can define what we need in terms that are politically viable.

Wiley Kitchens: My point is that if we are simplistic about it, diversion is going to be the name of the game. There are estuarine systems that function very well, essentially, on the rainfall that falls directly into the basin. There are a number on the coast of South Carolina that operate just this way and are very productive. We need not be overly simplistic.

Chris Tamke, Florida Department of Natural Resources: There has been quite a bit of comment about the larger estuaries; San Francisco Bay, Chesapeake Bay, Columbia River and a conspicuous absence of comment regarding a number of the smaller estuaries. I hope that the conference does not leave outsiders with the opinion that the small estuaries are less important because I think they are important, especially in the case of Florida, where we have a number of small estuaries. The cumulative effect of eliminating all of those would be at least as bad as eliminating one of the other ones. It also seems, with possibly the exception of the Apalachicola area, that you are most likely to maintain the natural salinity regime in some of the smaller estuaries where there are fewer problems than in, say, the Columbia River basin. If that is in fact the case, some of the smaller areas, which could also be more easily studied, could become models for the larger systems.

John Clark: If I remember rightly, when the old Federal water quality group did their national estuarine pollution survey in the late 1960's, they identified over 500 estuarine bodies in the United States. We certainly have a lot of smaller ones to attend to. I personally feel much more hopeful about being able to salvage and conserve the smaller ones than I do about some of the larger ones. We have perhaps 300 really typical and classical type estuarine resource units around the country, each of which should have a management plan right now.

Murray Walton, Wildlife Management Institute: The recommendations given earlier by Mr. Clark are very fine and we should not quibble over differences among individual estuaries. Certainly we should move forward on the political front, but I think we have a lot of opportunities on the administrative front. We could enforce NEPA better. We could enforce the Fish and Wildlife Coordination Act better. All administrative agencies could do a better enforcement job and the conservation organizations need to make a little stronger push in this area. The problem is not what one bay needs or what the other bay needs, the problem is estuarine protection.

John Clark: Thank you very much. That's good advice. Sometimes it is really hard to keep on target because there are so many needs to distract you.

Richard Bailey, Department of Housing and Urban Development: For the next conference, I think we are going to be spinning our wheels unless we involve two other groups. In the West, you have to get at the water that is going to farming. You should involve Water and Power Services to a greater extent in the next conference. In both the East and West, if you are talking about sedimentation, watersheds, and quality and quantity of water that comes down river, you are talking about the Soil Conservation Service. That agency is not represented here but SCS could do quite a bit on a national scale. They have the existing mechanism, if you get them involved with some of these goals.

John Clark: SCS has some new initiatives, going or proposed. I feel sure they would appreciate our help in pointing out the problems that many of the estuaries are suffering because of soil erosion. They are having problems getting anyone to take them seriously when they talk about cross compliance. We could help emphasize their case which would strengthen the demand on farmers to do what they should. But, there is one other problem. It is one thing to try to convince a farmer to keep the soil on his field for generations to come or to preserve soil nutrients, pesticides, and anything else he puts on the field for his own benefit. It is quite another thing to take on the job of handling the material that does leave the field before it gets to a water body. There you enter a whole different kind of motivation, another level of technology, and costs which the individual land owner is not really going to meet.

Richard Bailey: Unless you meet the problem at that level in the East, it will be non-point source pollution that is going to kill us. We lack a strategy and I think that strategy is going to be at the level of the individual large farmer or developer. The farmer is going to have to stop allowing his water out in the ditch directly from the farm even though he is the family farmer.

Bob Hayden, U.S. Fish and Wildlife Service: I want to reemphasize the need to quantify the inflow requirement of estuaries. This is very important everywhere and it is absolutely critical in San Francisco Bay right now because they are proceeding as if there is no problem. The number that seems to be generally accepted at this conference is 30 percent flow reduction as a threshold but in San Francisco we're at 50 percent. If we could have a conference where we could establish the authoritative state of knowledge regarding estuarine inflow requirements, this would be a very large benefit to us. I suggest that we have another conference a year from now and have national experts focus particularly on that. There is no reason that it could not be led by units of the Fish and Wildlife Service cooperating with others. I think Coastal Ecosystem Team could handle it within our existing programs.

John Clark: I think Fish and Wildlife has got something started here that they are not going to be able to ignore in the future. I hope so.

Richard Horowitz, Academy of Natural Sciences of Philadelphia: You stated one of your original recommendations twice. When you did so, you equated optimal and natural which is only a theoretical equation. We have even heard some evidence here that it is not necessarily true. We may get into trouble if we try to make that equation. In fact, some of our frustration may stem from trying. I think it would be a little better to think about natural, not because we believe it is optimal, but because we know it works for risk management.

Mike Rosengurt, Sanitation District of Los Angeles County: I cannot agree that Russian rivers are somehow different from American rivers. According to the Russian experience of the last 20 years, 30 percent is the critical limit for any kind of river. The Volga discharges about 200 kilometers cubed per year, the Danube 200, the Dnieper 54, and we found that if water withdrawals are more than 35 percent of the outflow, the salinity increases about two or three times, especially in the area of delta estuaries. The San Francisco Bay area has about 50 percent withdrawal and a salinity increase in the delta of about ten times and about twice in Suisun Bay and San Pablo Bay. I fear an ecological disaster if we cannot outline the requirements for the Nation.

Jess Matthews, Texas A & M University in Galveston: So many different government organizations are involved in estuaries that I wonder if any one organization can be given the function of establishing the quality and quantity of water and the priorities or limits that each estuary should have. I'm bringing this up in the sense of suggesting that a nongovernmental agency, such as the Conservation Foundation, be charged with the job. Requirements or recommendations could be funneled to that organization. More organizations might be willing to submit what they would consider their requirements if they were not submitting to a competing organization.

John Clark: The problem you raise is probably the major subject that we have to cope with to get anything going from this symposium. Of course, we'd really like to get conservation being done by the people that actually makes the changes and construct the projects, but if you are going to have the fox in the chicken coop, you had better make sure his stomach is full.

Walt Gallaher, U.S. Corps of Engineers, Dallas: I hope that we have another symposium on this subject next year and would suggest that we bring some examples of estuarine improvement successes. Even if the decisions were made without all the scientific facts, these examples could serve as nuclei or ideas for others around the country.

John Clark: I think that is a marvelous idea. Thank you very much, and I hope to see all of you next year.

SUMMARY AND RECOMMENDATIONS OF SYMPOSIUM

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John Clark

Conservation Foundation, Washington, D. C.

Norman Benson

U. S. Fish and Wildlife Service, Slidell, Louisiana

INTRODUCTION

The goal of the National Symposium on Freshwater Inflow to Estuaries was to review the management, planning, and scientific and technical problems associated with freshwater inflow to estuaries and to formulate recommendations to include freshwater inflow in the planning and management processes. Thus, the Symposium was organized to develop and assemble information and to propose action programs.

The Symposium revealed that, although the importance of estuaries has been recognized by Congress and others, few actions have been taken to protect them. As a society we find ourselves talking about the importance of estuaries and how they should be saved while our actions, or lack of action is the result of many causes: the complex nature of estuaries, the geographical differences in their requirements and man's effect on them, our often fragmented single-discipline and single-purpose approach toward them, and our willingness to act without a clear understanding of the ultimate effects of our actions. It was recommended that there should be a renewed nationwide mandate to recognize estuaries as resources of extremely high value, and that nationwide conservation objectives should be established that can be visualized and applied by the public, engineers, scientists and managers. Optimal salinity regimes should be established as conservation objectives for each estuary, with optional sediment and hydrologic regimes as related objectives.

The Symposium's opening plenary session described the high values of estauries to the Nation for recreation, food and aesthetics. Freshwater inflow problems were identified in Raritan Bay, Chesapeake Bay, southern Florida, the Gulf of Mexico, San Francisco Bay and the Columbia River estuary. The problems identified include the reduction of volume of freshwater inflow, modification of seasonal flow regimes, reduction of water quality, and alteration of sediment and nutrient content in freshwater inflow. It was emphasized that estuarine degradation and management must be dealt with more effectively if estuaries are to continue to produce the products and services that the Nation expects of them. The need to determine the effects of various types of management on estuarine ecosystems was emphasized. It was also pointed out that many estuary production processes and environmental problems are not directly related to freshwater inflow, and that ecosystem planning and management must consider all man-related actions that affect estuaries. Several speakers noted that problems exist in defining the freshwater needs of estuaries, and that widely recognized criteria are needed for setting ecological goals in estuaries. Because of the lack of data, the freshwater needs of many estuaries cannot compete with the more clearly defined needs of agriculture, industry and cities.

This review summarizes some of the pertinent research findings that were presented, some of the planning problems identified, specific recommendations that were presented in papers or in discussion, and general recommendations on how the protection of estuaries may be pursued. General conclusions are offered.

RESEARCH FINDINGS

The relations between freshwater inflow and biological production and processing in estuaries were described in many papers. Several papers emphasized the need for long-term (6 to 15 years) data before we can develop an understanding of estuarine ecosystems. However, a combination of data files and sophisticated prediction methods can be used to aid decisionmaking where insufficient time series data exist. The importance of temperature of river inflow on estuarine organisms was recognized in Chesapeake Bay for striped bass and in Louisiana for shrimp and oysters. Natural temperatures of incoming rivers are being altered by the passage of river water through power plants and by water being discharged from reservoirs and other water-control structures on rivers. In some areas the positive correlation between shrimp production and freshwater inflow has been shown but remains unexplained. Benthic infauna production was directly related to freshwater inflow and may be one reason for the positive correlation between freshwater inflow and shrimp production.

Drainage ditches in North Carolina increased coastal runoff rates which deleteriously affected shrimp production. Upper Chesapeake Bay salinities have decreased historically because of an increased rate of runoff due to the reduced amount of forested land in the watershed, but increased water diversion may reverse this trend. Changes in land use have influenced river flow in many areas.

Published results regarding water developments in rivers entering the Azov, Caspian, Black and Mediterranean seas in Europe and Asia all point to the conclusion that no more than 25 to 30 percent of the historical river flow can be diverted without disastrous ecological consequences to the receiving estuary. Comparable studies on six estuaries by the Texas Water Resources Department showed that a 32 percent depletion of natural freshwater inflow to estuaries was the average maximum percentage that could be permitted if subsistence levels of nutrient transport, habitat maintenance, and salinity control were to be maintained. The Second National Water Assessment, prepared by the U.S. Water Resources Council, produced data showing that several U.S. estuaries already have incurred depletion levels greater than those threshold levels. Several models were described or are under development for predicting the ecological effects of freshwater inflow in Texas, Chesapeake Bay and San Francisco Bay.

The importance of the salinity transition zone in estuaries for mineralization, mobilization, and release of nutrients from the substrate of estuaries was described. Remote sensing can be used to monitor salinity, chlorophyll a, temperature and suspended sediment in estuaries.

Studies on Potomac River water quality from 1920 to 1979 identified the importance of suspended sediment in preventing algae blooms where nitrogen and phosphorous levels in inflowing water have increased. Research in wetlands adjacent to a heavily developed resort area in Florida predicted that freshwater inflow can be partially restored through a combination of retention structures (small lakes) and spreaders to attain sheet flow into the estuary. The capability of predicting delta formation for several Louisiana estuaries exists and should facilitate planning over-dike freshwater inflow introductions.

All sections of the conterminous U.S. coast were covered in the research papers, but there were more papers from the Gulf of Mexico than from other coastal areas.

PLANNING

Planning problems and ideas were generated by many papers and in the discussion. Several speakers emphasized the need for multi-agency and interdisciplinary studies and planning efforts. Clearly defined ecological and development goals must be established for individual estuaries. These goals may describe types of habitats (e.g., intermediate and freshwater marsh in Louisiana) that are needed, desired organisms to be maintained, and uses of estuaries and freshwater supply by people. Management for protection of estuaries must be comprehensive; it must extend upstream and include water and land use. Although many models use finfish or shellfish production to evaluate the effects of freshwater inflow, several authors felt that it would be preferable to use community condition or ecological structure and processes to evaluate effects.

Comprehensive management must involve getting the support of many local, state, and Federal agencies, plus special interest groups. If they are properly used there are many state and Federal mandates and directives that can provide justification for providing freshwater inflow to estuaries.

In Louisiana it has been difficult to get local support for reintroducing freshwater inflow into estuarine habitats because the local and short-term demands are high, and long-term impacts, while beneficial, are foregone. Small-scale freshwater-introduction programs are being tried to demonstrate the values of maintaining more natural dispersal before large-scale programs are undertaken.

RECOMMENDATIONS

Specific recommendations were made by speakers and general recommendations were developed at the closing plenary session with significant audience participation. There is some overlap between the specific and general recommendations, but both are presented below. Some specific recommendations apply to restricted geographical areas.

Specific Recommendations

1. Baseline data files on individual estuaries should be established for use in identifying future ecological change.

2. Mission-oriented agencies responsible for developing management plans or for land acquisition and zoning in the coastal zone should establish draft priorities for their activities for the estuaries of the United States. These priorities should then be evaluated and tradeoffs developed by interagency groups, regional or state agencies so that the established priorities will serve environmental, commercial, urban, and other interests in a comprehensive manner.

3. Criteria for evaluating the freshwater needs of estuaries must be established on a national level. Criteria may be either purely physical or ecological, but physical criteria are easier to establish on a national level. Salinity must be considered because it is a fundamental ecological factor and is easily measured.

4. Refined methods for evaluating the economic and non-economic benefits of freshwater inflow to estuaries need to be developed. Beneficial uses of estuaries must be defined and justified more clearly if adequate fresh water is to be provided through water rights decisions.

5. Planning for freshwater inflow to estuaries should be based on the carrying capacity approach, but trend analysis may be used to identify change. Carrying capacity is defined as the capability level of the estuary units to produce essential ecosystem products and services.

6. The ecological effects and economic consequences of proposed inland water development projects must be tracked to and through the estuaries. Coastal ecological communities and estuarine values must be included in tradeoff analysis of upriver planning through impact assessment.

7. There needs to be a stronger and more effective use of existing state, regional, and Federal regulations and mandates to bring freshwater inflow into water planning.

8. The reintroduction of freshwater into estuarine ecosystems in the lower Mississippi River region should be primarily a Federal responsibility because most of the diversion of fresh water away from estuarine habitats resulted from Federal flood control and navigation projects.

9. Management and research programs on rivers and watersheds should be integrated with those for estuaries.

10. Information developed abroad showed that a reduction of over 25 to 30 percent of natural river flow resulted in disastrous ecological consequences in estuaries. Therefore, we suggest that (1) the U.S. Environmental Protection Agency give serious consideration to promulgating a standard for cessation of further consumptive depletion of natural freshwater inflow until it can be shown that additional depletion can be tolerated, and (2) that the U.S. Water Resources Council include as part of the President's proposed Independent Project Review Process a criterion for evaluating adherence to such a standard.

General Recommendations

At the final plenary session four general recommendations were presented and discussed. It was stated that although the importance of the estuaries has been recognized by Congress since the early 1960's and was stated explicitly in the passage of the Estuary Protection Act in 1968, few recommendations of professional groups have been acted on effectively to protect estuaries. One problem is that estuaries are so variable the scientists, engineers, and planners have not worked together effectively on a national level to reach a general consensus on how estuaries can be managed and protected. There has been some success at regional and state levels. An action program to protect estuaries is needed because of the extremely high productivity of estuaries and because they are vital to coastal and ocean ecosystems and to the Nation as a whole. Although such mandates as the Coastal Zone Management Act, National Environmental Policy Act, Clean Air Act and the Estuary Protection Act strive to protect estuaries, there is a lack of a clear mandate to protect them systematically and effectively. Accordingly, four general recommendations were developed at the symposium:

1. Estuaries are complex ecosystems that can be managed for common purposes. Some types of water use in estuaries will serve special purposes, but compromises can be worked out. Man-caused changes in freshwater inflow or other morphological or hydrological changes in estuaries must be evaluated as to how the changes will affect the structure and processes in estuarine ecosystems.

2. There should be a nationwide mandate to recognize estuaries as resources of extremely high value and worthy of protection.

3. Each estuary must be treated as a unit resource and must have its own management plan. We need, however, a conservation objective that can be applied to estuaries in general and that can be visualized by the political sector, the public, fishermen, engineers, planners, and scientists. We propose that optimal salinity regimes should be established as conservation objectives for each estuary with optional sediment and hydrological regimes as related objectives. These regimes shall recognize seasonal, annual, and historical variation. If these objectives are properly established and implemented, they will protect estuary ecosystem functions and processes. These conservation objectives shall serve as targets for planning and management in estuaries.

4. Finally, we should pursue these recommendations with governmental agencies, Congress, and elsewhere to bring the protection of estuaries as a national issue to be considered in all water development and management programs.

CONCLUSIONS

The symposium brought together people from a variety of disciplines and special interests to deal with the problem of tying together inland river management and land use planning for the protection of estuaries. It reviewed the progress that is being made to bring freshwater inflow to estuaries into water planning. It identified weaknesses in our data base that must be filled before detailed estuarine protection programs can be developed. It identified existing Federal and state legal and regulatory mandates that can be used to bring freshwater inflow into planning.

The diversity in estuarine ecosystems has prevented an effective nationwide program to establish criteria and objectives for estuarine protection. Also, the responsibility for environmental management and planning in estuaries is dispersed among many Federal and state agencies and local governmental units. Coastal zone management programs have not been generally effective in protecting estuaries.

The recommendations emphasized the need for a nationwide approach to develop criteria for the balanced uses of estuaries which would serve to preserve and enhance their environmental values. The responsibility for protecting estuarine ecosystems needs to be defined more clearly at the Federal level so that all upstream projects affecting water supply must be evaluated relative to their effects on estuaries. Finally, efforts must be made to protect estuarine ecosystems as a nationwide policy.

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The Proceedings include 76 scientific and management papers on the institutional and management problems of providing freshwater inflow to estuaries, documented ecological effects in estuaries of modifying freshwater inflow, and suggested measures to bring freshwater inflow into water planning. Discussion material is included in the Proceedings. The problems of freshwater inflow include reduction in volume due to inland water diversions, modification of seasonal flow regimes, reduction in water quality and alteration of sediment and nutrient content. Freshwater inflow problems were identified in Raritan Bay, Chesapeake Bay, southern Florida, the Gulf of Mexico, San Francisco Bay, and the Columbia River estuary. Estuaries should be recognized in water policy decisions as high value resources for food production, recreation, aesthetics, and urban and industrial development. For planning it was recommended that optimal salinity regimes be established for the nation's estuaries with optimal sediment and hydrologic regimes as related objectives. Several papers and discussion stated the need to develop improved methods for evaluating the effects of inland river development programs on estuarine ecosystems.

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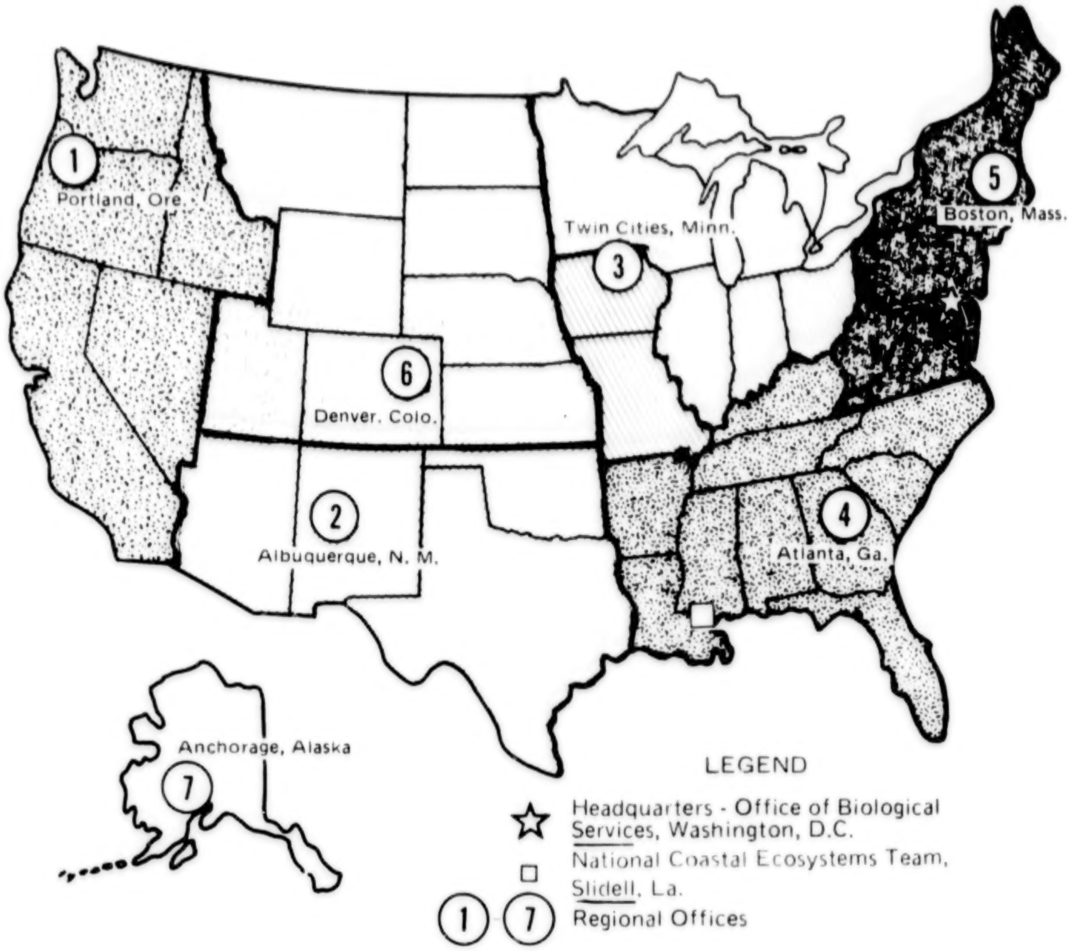

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